Studio per un prototipo di interferometro di Fabry-Pérot per applicazioni spaziali

Study of a Fabry-Pérot interferometer prototype for space applications

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Abstract

In questo lavoro di tesi specialistica viene presentato lo studio per un interferometro di Fabry-Pérot in corso di sviluppo presso il Laboratorio di Fisica Solare dell’Università agli studi di Roma Tor Vergata. In particolare, durante il lavoro di tesi, mi sono occupato della definizione dei requisiti di posizionamento nanometrico della cavità ottica. In tale ambito ho sviluppato un programma di simulazione del Fabry-Pérot e ho calibrato sperimentalmente il sistema piezo-capacitivo servocontrollato.

Il prototipo verrà usato per effettuare dei test su banco ottico della qualità ottica meccanica e del controllo elettronico. Servirà inoltre come base per lo sviluppo di un prototipo da volo per applicazioni in campo astronomico da satellite. Viene presentato l’interferometro di Fabry-Pérot all’interno del quadro degli spettroscopi per uso astronomico, con i suoi vantaggi e svantaggi. Viene trattata nel dettaglio la teoria dell’interferenza di fasci multipli nel caso ideale e le limitazioni di uno strumento reale. Vengono prese in considerazione le possibili applicazione da terra e dallo spazio di un tale strumento nei campi dell’Astronomia, con particolare attenzione al caso dello studio del Sole.

Viene inoltre descritto il prototipo in corso di sviluppo e il funzionamento elettromeccanico del controllo della cavità ottica, con i due movimenti di regolazione micrometrica e macrometrica e i sensori capacitivi di controllo. È inoltre riportato il software di controllo sviluppato. Sono infine mostrati i risultati dei test effettuati sugli apparati elettromeccanici di controllo.

In this master thesis we describe a study for a Fabry-Pérot interferometer being developed at the Laboratory for Solar Physics of the University of Rome Tor Vergata. In particular, during the thesis work, I have defined the requirements for nanometric positioning of the optical cavity. In this context, I developed a Fabry-Pérot simulation program and I have calibrated experimentally the piezo-capacitive servo system.

The prototype will be used to perform optical bench tests of the mechanical and optical quality and of the electronic control. It will also serve as the basis for the development of a flight prototype with applications in astronomy by satellite. The Fabry-Perot interferometer is presented within the framework of astronomical spectroscopy, both advantages and disadvantages are underlined. The theory of multiple beams interference is discussed in detail in the ideal case; theoretical limitations of a real instrument are presented too. We take into account
the possible ground and space applications of this instrument in the fields of Astronomy, with particular attention to the study of the Sun.

We also describe the prototype under development and operation of the electromechanical control of optical cavity, with details of coarse and fine adjustment and capacitive sensors control. The control software developed is also reported. Finally, the results of tests carried out on the electromechanical control devices are shown.
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Thanks also to LightMachinery for valuable help with the optical components.
Lo studio delle stelle fisse quanto è stato finora importante per la teoria de’ movimenti celesti, altrettanto è stato limitato per le ricerche fisiche. Tutto finora si è ridotto a esaminarne il colore, l’intensità della luce e la varibilità.

Ma la scoperta della spettrometria ha fatto di questo studio uno de’ più vaghi, svariati e anche dilettevoli ed importanti che possono trovarsi. La varietà delle tinte delle stelle è accompagnata da una corrispondente distinzione de’ loro colori elementari, e da una differenza di righe spettrali: e queste essendo mirabilmente collegate colla natura della materia che arde in quegli astri e li costituisce, ci viene per tal mezzo somministrato come conoscere la natura di quelle sostanze di cui sono formati.

Padre Angelo Secchi

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The Six Phases of a Project:

1. Enthusiasm,
2. Disillusionment,
3. Panic,
4. Search For The Guilty,
5. Punishment Of The Innocent,
6. Praise and Honours For The Non-Participants.

Anonymous

Cited by Philip Hobbs in Building Electro-Optical Systems
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Chapter 1

Introduction: Spectro-imaging in Solar Astrophysics

The Sun is the only stellar object that can be resolved from Earth with high spatial, time and spectral definition, making it the key to much of the current astrophysical understanding. Furthermore, our star is the only place in the solar system where hot plasma with unique features can be found and directly observed. The Sun remains a Rosetta Stone for all other stars to understand turbulent convection, dynamics and fine processes not yet directly detectable on other stars. Nevertheless, some fundamental processes undergoing in the Sun atmosphere are not yet fully understood:

- How does the magnetic field emerge to the surface and evolve?
- How is the energy transported from the photosphere to chromosphere and corona?
- How is the energy released and deposited in the upper atmosphere?
- Why does the Sun have a hot chromosphere and a million degree corona?

This short list is intended to point out only some of the solar issues related to the directly observable layers. The role of MHD phenomena, like Alfvén waves, is becoming of great interest in the last years both theoretically and observationally. The magnetic reconnection, the coronal heating remain unsolved problems and main research themes. Increasing the spatial and the spectral resolution is fundamental to reconstruct tomographically the solar atmosphere and in this way try to understand those processes.
1.1 Spectral Lines in Solar Physics

Whenever a photon of the right energy hit an atom or ion in the solar atmosphere, the electrons of the atom/ion element change their energetic level absorbing the photon’s energy. This process takes place where there are the suitable condition to adsorb light at a certain wavelength, so only in a certain atmospheric layer. After some time in this excited level, the electrons come back to the previous energetic status re-emitting the photon. Re-emission happens with no preferential direction, resulting in a light intensity decrease along the light of sight for a certain wavelength: an absorption spectral line.

![Solar spectrum atlas from 300 nm to 1000 nm](Kur04)

This can be described (see Sti02) as a change in the opacity $k_\nu$ of the medium in a certain wavelength. If we introduce the optical depth at frequency $\nu$:

$$d\tau_\nu = -k_\nu \rho dr$$ (1.1)

The intensity variation can be described using radiative transfer equation

$$\cos \theta \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu$$ (1.2)

where $I_\nu$ is the intensity for unit frequency, $S_\nu$ is the source function and $\theta$ is the angle to the local vertical direction. Optical depth can be divided in contributions from continuum and absorptions lines

$$d\tau_\nu = (1 + \eta_\nu) d\tau_\nu$$ (1.3)

where $\eta_\nu = k_l(\nu)/k_c(\nu)$ is the ratio between continuum and line opacity values. If we assume local thermodynamic equilibrium (LTE) of the medium along the line of sight, we can use Planck distribution as source function: $S_\nu = B_\nu$. If we integrate over $\tau_\nu$ at disc center we have

$$I_\nu = \int_0^\infty (1 + \eta_\nu) B_\nu \exp \left( -\int_0^\tau (1 + \eta_\nu) d\tau' \right) d\tau$$ (1.4)
Transition from optically thin to optically thick in a certain wavelength depends on the position on the Sun and the thermodynamic state of the plasma, as well as on the chemical composition of the medium. Some of the lines observed in the Sun spectrum derive from the photosphere, like the Fe I at 709.0 nm (see fig. 1.2). Some strong lines derives instead from higher layers in solar atmosphere, such as the H-alpha or the Ca II K line (see fig. 1.3). Solar spectrum atlas is shown in figure 1.4. Ca II doublet and H-alpha lines are visible around 395 nm and 656 nm respectively.

Figure 1.2: Solar spectrum: Fe I 709.0 nm, photospheric line

Figure 1.3: Solar spectrum: Ca II K line at 393.37 nm, chromospheric line

When we observe the Sun in such lines it is possible to obtain information on the corresponding layer in the atmosphere. Observing different absorption lines make it possible to reconstruct the solar atmosphere tomographically (fig 1.5).

Spectral shifts of absorption lines with respect to laboratory calibrated sources may identify dynamical processes occurring, as Doppler shifts $\Delta \lambda_D = \frac{\Delta v}{c}$, as well as gravitational redshift $\Delta \lambda_G = \frac{\lambda GM_\odot}{2r_\odot c^2}$. In this way, it is possible to reconstruct the line of sight (LOS) velocity fields and to study solar atmosphere dynamics phenomena.
Figure 1.4: Solar spectrum atlas from 300 nm to 1000 nm \[\text{Kur04}\]

Figure 1.5: Absorption line mechanism: tomography reconstruction
Information about the solar interior can be derived from spectral lines analysis too. Until the last scatter in the solar photosphere, the light cannot go straight, finally reaching the instrument, due to the many interactions with solar plasma. In this way any information previous the last scatter is canceled. Nevertheless, analysing the p-modes waves from the LOS velocity fields, it is possible to investigate density, opacity, temperature of the layers beneath the photosphere. The Helioseismology analysis of free oscillations and is the analogous of the seismology techniques used to investigate Earth interior.

Plasma physics is the basis of many observational aspects of our star seen in details: the magnetic field generated by the solar dynamo, the plasma convection and the heat transport, the solar cycle and the sunspots, the active regions, the flares and the coronal mass ejections, the solar storms and the Sun-Earth interaction. At the base of these phenomena is the interaction between the plasma medium and the magnetic field. For this reason, in order to understand all the phenomena previously mentioned, it is necessary to record information on the magnetic field. It can be obtained from the Zeeman splitting of spectral lines. However, this is possible only for a sufficiently strong field. Otherwise it is possible to use the effect of polarization of the Zeeman components. You can then reconstruct the direction and intensity of the magnetic field using Stokes profiles of Zeeman sensible absorption lines. With the introduction of such a new quantity to be measured, spectroscopy techniques have been improved in spectropolarimetry.

Those previously mentioned are just two examples to underline the importance of spectroscopy in modern solar Physics. Both of them require the imaging of a certain field of view at different wavelengths, in order to retrieve all the spectral points needed to sample a line profile. This means that we are interested in a 3D datacube with two spatial and one spectral dimensions, acquired at the highest possible temporal cadence. Things become even more complicated if we are interested in the magnetic field too, requiring the acquisition of the four Stokes profiles and so multiplying by four the number of measures. The first difficulty to overcome in the instrumental setup is the fact that the detectors in use are bidimensional. With this point of view fixed, spectroscopy combined with polarimetry and a high spatial resolution through imaging is the key instrument in solar astrophysics knowledge.

1.2 Spectroscopy: Observational Aspects

A spectrometer is able to select a certain wavelength and to record its intensity. You can do this by dispersing different components of the spectrum, positioning them in spatially different parts of the sensor. Another way is to filter incoming light such that only a small part of the spectrum can pass. In both cases, the goodness of the instrument lies in the ability to distinguish spectral features. Given a certain wavelength of interest $\lambda$ and the smallest spectral
interval that can be resolved $\Delta \lambda$, the resolving power $\mathcal{RP}$ of the instrument is defined as:

$$\mathcal{RP} = \frac{\lambda}{\Delta \lambda}$$  \hspace{1cm} (1.5)

There are a certain number of observational aspects that have to be taken into account during spectroscopy observations. As we have seen one of the biggest issues is the fact that we are expanding information from single points or extended sources, having some troubles in recording all data with the sensor. This leads us to some trade-off between the amount of data and the temporal cadence.

As we are usually interested in dynamical processes occurring on a certain time scale, the detecting time of all the data required must be less than that. In the case of phenomena characterized by typical different time frequencies, instrumental time frequency should be twice the maximum frequency to fulfil the Nyquist theorem. This is a real challenge in case of phenomena that requires image information too, because they are extended objects, as is the case of solar atmosphere dynamics.

Other related issues are the long exposure times, required by faint sources. In that case, the light flux must be adjusted to fit the required instrument time scale sizing the collective power of the telescope or choosing an instrument with appropriate transparency. The latter is a really critical parameter for an instrument that has to split the light in all the different components (as a long slit spectrometer), or has to discard most of the photons letting pass only the desired wavelengths (the case of a tunable filter). Both these kinds of instruments should try to maintain unchanged the photon flux in the selected band, in order to have maximum possible sensitivity.

Given the high relative brightness of the sun, the lack of photons in this kind of observations might not seem a problem. However, if we consider a realist count of the recorded photons, this may change the point of view. Given an observed area of $0.3'' \times 0.3''$ on the photosphere using a $60 \text{ cm}$ telescope and a high resolution spectrograph ($1 \text{ pm}$ of bandwidth at $\lambda = 500 \text{ nm}$), an exposure time of $1 \text{ ms}$ and a total efficiency of the whole system of $\sim 1\%$, only 400 photons are detected [Sti02]. Photon shot noise in this case is 5%, but if we are interested in observing a sunspot umbra, where the intensity is an order of magnitude less, or the core of an absorption line, or both of them together, this can lead to have just 3 or 4 photons available. One could be even interested in observing polarization signals of the order of 1% of the total. For these reasons, high throughput instrument are necessary in solar physics too.

Other important parameters are the field of view and the spatial resolution as they respectively set the lowest and maximum spatial frequencies detectable with the instrument. Focusing on proper spectral characteristics, we have already mentioned the resolving power. Beside this, the observational band is also important, as it sets the limits of detectable wavelengths. Another important spectral property is the instrument stability. If the spectral calibration is not stable enough to be considered fixed through all the time of data-taking, this
can affect all observations. Spectral drifts must be avoided as they are not easily distinguishable from other shifts derived from physical phenomena, as Doppler shifts: \( \frac{\Delta \lambda}{\lambda} = \frac{v}{c} \).

For example a shift of 0.1 nm at a wavelength of 550 nm corresponds to a false Doppler signature equal to 55 m/s.

### 1.3 Spectroscopy vs Spectro-imaging

If we observe at a wavelength corresponding to an absorption line, we can obtain information on the layer of the atmosphere where absorption undergoes. In order to reconstruct in 3D a region of interest of the solar atmosphere, we need both spatial information (ie imaging) and spectral information of every point of that region. What we want is a data cube in which every horizontal plane is an image of the region of interest at a different wavelength.

This request is substantially different from what a spectrograph can normally obtain. Since a spectral analysis requires the expansion of the information contained in a single point in a mono-dimensional strip, restricted region of interest are usually selected from the field of view to be examined. In the case of solar atmosphere dynamic, scientific investigation of astrophysical phenomena from an extend source requests a full field of view to be investigated. This implies the transition from point-like object spectroscopy to full image spectroscopy.

![Data cube reconstruction](image)

**Figure 1.6:** Data cube reconstruction. Different kinds of spectrometers, from [MAR+10]
long-slit spectrometer, it collects all the data cube moving the 1D slit along the solar surface. There are also other ways of cutting the cube, for example the double-pass spectroscopy. For a complete discussion on the topic we refer to \[MAR^{+10}].

Figure 1.7: Data cube reconstruction. From left to right: Fabry-Pérot, long-slit, double-pass spectroscopy.

None of them is capable to retrieve all the data in a single operation, as the sensor is bidimensional. The acquisition time becomes the key issue. In fact, if the instrument spends more time to collect all the data than the typical evolution time of the phenomena, we won’t read the cube as a whole. One side of the cube would be related on the initial physical condition of the Sun, but not the other side, because the system would have changed his condition in the meanwhile. Fast instruments capable of freezing all the physical conditions in a cube before the system can evolve and then reconstruct the time evolution with a series of data-cube are fundamental.

1.4 Spectroscopy Techniques

There is a variety of instruments used in spectroscopy. Here the attention is focused on the most used two: long slit spectrometry, with a digression on his variant double pass spectroscopy, and the Fabry-Pérot interferometer, subject of study of this thesis. Here there are some definitions used in the next sections:

- Entrance focal plane intensity: \( f(x, y; \lambda) \)
- Exit focal plane intensity: \( F(X, Y) \)
- Focal plane extension: \([x_0, x_n][y_0, y_n]\)
- Wavelength interval: \([\lambda_0, \lambda_n]\)

Long Slit spectroscopy

In a long slit spectrometer, a grating is introduced in order to disperse the light along the horizontal axis of the exit focal plane of the instrument. The grating is characterized by a dispersion relation:

\[
X = x + \frac{\lambda}{d}
\]  

(1.6)
where \( d \) is the linear dispersion of the order of the grating. If no other device is introduced along the optical path, the resulting intensity on the exit focal plane is a mixing of spectra from all the points of the conjugated horizontal line.

Figure (1.8) represents this mixing. On the left there is an example of an entrance focal plane with an image from the telescope. In the scheme, this plane is represented again by the bold line in the central part of the image from where three sample light rays depart. The rays strike on the vertical grating (the other bold line on the right) and the light is dispersed along the horizontal direction with a linear dispersion \( d_1 \). Different spectra are superimposed on the exit focal plane (upper bold line) and every pixel of the sensor in that position will collect light rays from all the points of the conjugated row of the entrance focal plane. Each ray will have a different wavelength.

![Figure 1.8: Spectra superposition. On the left a quiet region of solar photosphere](image)

The calculation of the intensity on the exit focal plane \( F(X, Y) \) will result either in an integral over the contribution of different pixel of the entrance focal plane (1.7) or in the integral over the different wavelength of the incident light (1.8).

\[
F(X, Y) = \int_{x_0}^{x_n} \int_{y_0}^{y_n} \int_{\lambda_0}^{\lambda_n} dxdy\lambda \delta(x + \frac{\lambda}{d_1} - X)\delta(y - Y)f(x, y, \lambda) = \\
= \int_{x_0}^{x_n} dx f(x, Y, d_1(X - x)) = (1.7) \\
= \int_{\lambda_0}^{\lambda_n} d\lambda f(x - \frac{\lambda}{d_1}, Y, \lambda) (1.8)
\]

If a mask is now inserted on the entrance focal plane, a single line is selected and in every point of the exit focal plane we will receive light at a single wavelength. In this treatment we omit the issues regarding the overlapping of different spectral orders for simplicity.

The introduction of the slit is translated as an additional \( \delta(x - x_i) \) term in the integral (1.7) which enables to solve the integral obtaining the following relation

\[
F(X, Y) = \int_{x_0}^{x_n} \int_{y_0}^{y_n} \int_{\lambda_0}^{\lambda_n} dxdy\lambda \delta(x + \frac{\lambda}{d_1} - X)\delta(y - Y)\delta(x - x_i)f(x, y, \lambda) = \\
= \int_{x_0}^{x_n} dx f(x, Y, d_1(X - x))\delta(x - x_i) = f(x_i, Y, d_1(X - x_i)) (1.9)
\]
In order to scan the entire entrance focal plane the slit mask is moved horizontally after every acquisition step.

Figure 1.9: Long slit effect on the exit focal plane

Figure 1.10: Example of a spectrum from a long slit device
Double Pass Spectroscopy

If we come back to the dispersion relation without the mask, we can see that we could solve the integral also operating an integration over $\lambda$ instead that over $x$, as long as we can find a physical device that could do such operation along the optical path.

The main idea of a double-pass spectrometer is that on a point of the exit focal plane, we do have a mixing of photons from different position of the image, but each photon is characterized by a different wavelength depending on the original position on the image. The dispersion relation (1.6) let us know how this phenomenon is working. This property can be used to solve the superposition of different spectra. In fact, if a slit is put on the exit focal and the light is dispersed again with a second grating, we obtain on a second exit focal plane a disentangled image \[\text{Lop}\]. From a single vertical line it is possible to reconstruct all the field of view. We must point out that every column of this final image is characterized by a different wavelength so that on the vertical axis we have spatial information as in the entrance focal plane while, on the horizontal axis there is a mixing of spatial and spectral information.
Figure 1.11: From top to bottom: (a) spectra superposition; (b) exit focal plane masking; (c) second dispersion and final imaging: wavelength variation along the exit field of view
In the analysis of the double-pass spectrometer a second exit focal plane $F(W,Z)$ is needed, which describes the final output intensity function of the instrument.

$$F(X,Y) = \int_{x_0}^{x_n} \int_{y_0}^{y_n} \int_{\lambda_0}^{\lambda_n} dx dy d\lambda \delta(x + \frac{\lambda}{d_1} - X)\delta(y - Y)f(x,y,\lambda) = \int_{\lambda_0}^{\lambda_n} d\lambda f(x - \frac{\lambda}{d_1},Y,\lambda)$$

$$F(W,Z) = \int_{X_0}^{X_n} \int_{Y_0}^{Y_n} dXdY \delta(Y - Z)\delta(X + \frac{\lambda}{d_2} - W)\delta(X - X_i)F(X,Y) = \int_{X_0}^{X_n} \int_{Y_0}^{Y_n} \int_{\lambda_0}^{\lambda_n} dXdY d\lambda \delta(Y - Z)\delta(X + \frac{\lambda}{d_2} - W)\delta(X - X_i)f(x - \frac{\lambda}{d_1},Y,\lambda) = f(X_i - \frac{d_2}{d_1}(W - X_i), Z, d_2(W - X_i))$$

As we can see from the above equation (1.11) the simplest way of dispersing again the light is through the same grating ($d_1 = -d_2$) so that equal linear dispersion makes the final relation for the intensity even easier. The name “double-pass” for this kind of instruments derives exactly from this double use of the same grating.

**Fabry-Pérot**

A Fabry-Pérot is an instrument based on multiple beam interferometry. It is briefly introduced here to be compared with the previously mentioned spectroscopic techniques, while the next chapter contains complete information on this kind of spectrometer. A Fabry-Pérot consists of two flat plates which create an optical cavity. The two optical surfaces have a high reflectivity obtained with a dielectric coating. The cavity acts as an optical resonator, multiple reflections occur inside causing interference between the beams of light depending on the optical path difference ie the gap between the plates. In this way, the interferometer allows transmission of light at well-defined wavelengths. The instrument is called a Fabry-Pérot Etalon if the gap between plates is fixed, a Fabry-Pérot interferometer if the gap is adjustable and therefore the transmission wavelengths can be changed.

A spectrometer based on tunable filter is a solution to the problem of collecting both spatial and spectral information. In this case every image taken is nearly monochromatic and we can change quickly the wavelength of the observation. In this way it is possible to scan all the absorption lines, pixel by pixel, sampling it at different spectral points.

Defining an entrance focal plane of a spectrometer as the primary focal area of the telescope, characterized by an intensity function $f(x, y; \lambda)$, we are able to calculate the intensity function on the exit focal plane of the instrument, $F(X, Y)$. 

$$F(X, Y) = \int_{x_0}^{x_n} \int_{y_0}^{y_n} \int_{\lambda_0}^{\lambda_n} dx dy d\lambda \delta(x + \frac{\lambda}{d_1} - X)\delta(y - Y)f(x,y,\lambda) = \int_{\lambda_0}^{\lambda_n} d\lambda f(x - \frac{\lambda}{d_1},Y,\lambda)$$

$$F(W,Z) = \int_{X_0}^{X_n} \int_{Y_0}^{Y_n} dXdY \delta(Y - Z)\delta(X + \frac{\lambda}{d_2} - W)\delta(X - X_i)F(X,Y) = \int_{X_0}^{X_n} \int_{Y_0}^{Y_n} \int_{\lambda_0}^{\lambda_n} dXdY d\lambda \delta(Y - Z)\delta(X + \frac{\lambda}{d_2} - W)\delta(X - X_i)f(x - \frac{\lambda}{d_1},Y,\lambda) = f(X_i - \frac{d_2}{d_1}(W - X_i), Z, d_2(W - X_i))$$
A Fabry-Pérot spectrometer selects a single wavelength. Neglecting instrumental bandwidth, this is represented by $\delta(\lambda - \lambda_i)$

$$F(X, Y) = \int_{x_0}^{x_n} \int_{y_0}^{y_n} \int_{\lambda_0}^{\lambda_n} dx dy d\lambda \delta(x - X) \delta(y - Y) \delta(\lambda - \lambda_i) f(x, y, \lambda) = f(X, Y, \lambda_i)$$  \hspace{1cm} (1.13)

The result is that in every position of the exit focal plane the intensity is equal to the entrance intensity at the same position, limited to selected wavelength.

**Fabry-Pérot vs Gratings Spectrometers**

Jaquinot in 1954 has compared Fabry-Pérot and gratings spectrometer transparency, having the same instrumental features fixed [Her88, chapter 5]. Both of them are operated at a resolving power $R_P$. For a grating spectrometer we consider an angular height $\beta$ and an angular dispersion $D$. Ignoring diffraction effects, the maximum flux received by a grating spectrometer is

$$\Phi_g = \tau I A R S^{-1} \beta^2 \sin \psi$$  \hspace{1cm} (1.14)

where $A$ is the grating area, $\psi$ is the blaze angle of the grating, $I$ is the source irradiance and $\tau$ accounts for transmission losses in the instrument. For the Fabry-Pérot spectrometer the flux is [Her88, chapter 2, 5]

$$\Phi_{fp} = \tau I A \pi^2 [2.8 R S]^{-1}$$  \hspace{1cm} (1.15)

The ratio of the flux received by the Fabry-Pérot spectrometer to that received by the grating spectrometer is (for $\psi = 30^\circ$)

$$P = \frac{\Phi_{fp}}{\Phi_g} = 3.4 \beta^{-1}$$  \hspace{1cm} (1.16)

Since, for a very luminous grating spectrometer $\beta$ seldom exceeds a value of 0.1, equation 1.16 shows the Fabry-Pérot spectrometer to be the most efficient of these two spectrometers by a factor of at least 30. This rather large factor is the reason why the Fabry-Pérot is attractive for high resolution studies, because the sources used for this kind of investigation are usually weak.
Chapter 2

Fabry-Pérot Interferometer Theory and Applications

2.1 Multiple Beams Interferometry Theory

We present here the theory behind an ideal plane parallel Fabry-Pérot interferometer, following the approach used in [Bor99] [Fow90] [Her88]. The idea is to produce an interference pattern between multiple mutually coherent beams. They are produced splitting a single plane wave dividing its amplitude with a couple of partially reflecting mirrors. Every time the beam encounters one of the two optical surfaces the light is partially reflected and partially transmitted. Multiple reflections occurs inside the two surfaces leading to an infinite number of rays departing from the interferometer in both the transmitted and reflected directions. Contiguous beams differ for a constant phase; this causes the interference.

Figure 2.1: Multiple reflections interference produced by two plane parallel mirrors
The optical surface is here considered infinitely thin and for general purpose we consider a medium with refracting index \( n' \) inside the two mirrors while outside the refracting index is \( n \). Some quantities used are here defined:

- \( S \): signal plane parallel wave;
- \( n \): refraction index outside the mirrors;
- \( n' \): refraction index inside the mirrors;
- \( r \): reflection coefficient inside \( n \) medium;
- \( t \): transmission coefficient going from \( n \) to \( n' \) medium;
- \( r' \): reflection coefficient inside \( n' \) medium;
- \( t' \): transmission coefficient going from \( n' \) to \( n \) medium;
- \( d \): distance between the mirrors;
- \( E_0 \): electric vector complex amplitude of the incident wave;
- \( \lambda_0 \): vacuum wavelength
- \( \theta \): incidence angle
- \( \theta' \): incidence angle inside \( n' \) medium

In case of a Fabry-Pérot used in air or in the vacuum of a spacecraft there is only one refracting index and \( n = n' \) so that \( \theta = \theta' \).

The amplitudes of the reflected beams are then

\[
rE_0, \quad tt'rE_0, \quad tt'r^3E_0, \quad tt'r^5E_0, \quad \ldots, \quad tt'r^{2p-3}E_0 \quad (2.1)
\]

While the amplitudes of the refracted beams are

\[
\quad tt'E_0, \quad tt'r^2E_0, \quad tt'r^4E_0, \quad tt'r^6E_0, \quad \ldots, \quad tt'r^{2(p-1)}E_0 \quad (2.2)
\]

We can than define

\[
\begin{align*}
tt' &= T \\
r &= -r' \\
r^2 &= r'^2 = R
\end{align*}
\]

where \( T \) is the transmittance and \( R \) the reflectivity of one partially reflecting surface.
Figure 2.2: Illustration of the optical path difference ($ABC$) between two beams

The path difference is

\[
ABC = AB + BC \\
BC = s \frac{d}{\cos \theta'} \\
AB = OB - OA \\
OA = \sqrt{OC^2 - AC^2} \\
OC = 2s \sin \theta' \\
OA = \sqrt{4s^2 \sin^2 \theta' - s^2 \sin^2(2\theta')} = 2s \sin \theta' \sqrt{1 - \cos^2 \theta'} = 2ssin^2 \theta' \\
ABC = 2s - 2s \sin^2 \theta' = 2s \cos^2 \theta' = 2d \cos \theta'
\]

The phase difference due to the optical path between two adjacent rays is then

\[
\delta = \frac{4\pi}{\lambda_0} n' d \cos \theta'
\] (2.4)

After every reflection there is an additional phase difference $\delta_r$. Depending on the mirror material this phase can be $\delta_r = 0, 2\pi$ for a dielectric film or any value for a thin metal film [Fow90]. The total phase difference is then

\[
\Delta = \delta + \delta_r
\] (2.5)
If all the transmitted amplitudes are summed up together we hence obtain

\[ E_T = E_0 T + E_0 T R e^{i\Delta} + E_0 T R^2 e^{i2\Delta} + E_0 T R^3 e^{i3\Delta} + \ldots \] (2.6)

that is a geometric series with ratio \( Re^{i\Delta} \). Summing all together we obtain

\[ E_T = \frac{E_0 T}{1 - Re^{i\Delta}} \] (2.7)

The total transmitted intensity is now computed as

\[ I_T = |E_T|^2 \quad \text{with} \quad I_0 = |E_0|^2 \] (2.8)

\[ I_T = I_0 \frac{T^2}{|1 - Re^{i\Delta}|^2} \] (2.9)

The denominator term is now manipulated as follow

\[ |1 - Re^{i\Delta}|^2 = (1 - Re^{i\Delta})(1 - Re^{-i\Delta}) \]
\[ = 1 - R(e^{i\Delta} + e^{-i\Delta}) + R^2 \]
\[ = 1 - 2R \cos \Delta + R^2 \]

and using: \( \sin^2 \frac{\Delta}{2} = \frac{1}{2}(1 - \cos \Delta) \) \( \Rightarrow \) \( \cos \Delta = 1 - 2\sin^2 \frac{\Delta}{2} \)
\[ = 1 - 2R(1 - 2\sin^2 \frac{\Delta}{2}) + R^2 \]
\[ = 1 - 2R + 4R \sin^2 \frac{\Delta}{2} + R^2 \]
\[ = (1 - R)^2 + 4R \sin^2 \frac{\Delta}{2} \]
\[ = (1 - R)^2[1 + \frac{4R}{(1 - R)^2} \sin^2 \frac{\Delta}{2}] \] (2.10)

\[ I_T = I_0 \frac{T^2}{(1 - R)^2 \left[1 + \frac{4R}{(1 - R)^2} \sin^2 \frac{\Delta}{2}\right]} \] (2.11)

We can define a peak constant

\[ C_{PEAK} = \frac{T^2}{(1 - R)^2} \] (2.12)

For a real surface the incident light is not only reflected and refracted, but even partially absorbed. So we have

\[ A + T + R = 1 \] (2.13)

and the peak constant becomes

\[ C_{PEAK} = \left(\frac{1 - A - R}{1 - R}\right)^2 = \left(\frac{1 - A}{1 - R}\right)^2 \] (2.14)
If $A$ is small enough to be neglected we have that $C_{PEAK} \simeq 1$ and equation 2.11 can be simplified, obtaining

$$I_T = I_0 \frac{1}{1 + F \sin^2 \frac{\Delta}{2}}$$  \hspace{1cm} (2.15)$$

having defined the coefficient $F$ as

$$F = \frac{4R}{(1 - R)^2}$$  \hspace{1cm} (2.16)$$

On the other side, for the reflected light we have

$$I_R = I_0 \frac{F \sin^2 \frac{\Delta}{2}}{1 + F \sin^2 \frac{\Delta}{2}}$$  \hspace{1cm} (2.17)$$

Reminding that here we have set $A \simeq 0$, energy must be conserved and this is clear if we sum the transmitted and reflected intensities

$$\frac{I_T}{I_0} + \frac{I_R}{I_0} = \frac{1}{1 + F \sin^2 \frac{\Delta}{2}} + \frac{F \sin^2 \frac{\Delta}{2}}{1 + F \sin^2 \frac{\Delta}{2}} = 1$$  \hspace{1cm} (2.18)$$

**Interference Maxima**

If we now focus on the transmitted light and equation 2.15 is clear that the interference creates peaks. Figure 2.3 shows the interference pattern created focusing with a lens the transmitted light. Every bright ring corresponds to an order of interference. From 2.15 is clear that we have maxima for a phase difference $\frac{\Delta}{2} = \pi$ or an integral multiple of $\pi$. If we now consider a dielectric film, the $\delta_r$, which is equal to 0 or $2\pi$ can be neglected and we have from 2.4

![Figure 2.3: Interference ring pattern obtained imaging the Fabry-Pérot transmitted ligth of a detuterium lamp](image-url)
$$2m\pi = \delta = \frac{4\pi n'd\cos \theta'}{\lambda_n} \Rightarrow \sin^2 \frac{\Delta}{2} = 0$$
$$m = \frac{2n'd\cos \theta'}{\lambda_n}$$  \hspace{1cm} (2.19)

where \( m \) is the order of interference. The intensity at a maximum is equal to

$$I_{MAX} = \frac{I_T(MAX)}{I_0} = \frac{T^2}{(1-R)^2} = C_{PEAK} = 1 \quad \text{for} \quad A \simeq 0$$  \hspace{1cm} (2.20)

If we take into account the absorption term we have

$$I_{MAX} = C_{PEAK} = \left(\frac{1-A-R}{1-R}\right)^2 = \left(1 - \frac{A}{1-R}\right)^2$$  \hspace{1cm} (2.21)

In the minima the phase difference is \( \frac{\Delta}{2} = \frac{\pi}{2} \) or an integral multiple of it, \( \sin^2 \frac{\Delta}{2} = 1 \) and from equation [2.11] the intensity is

$$I_{MIN} = \frac{I_T(MIN)}{I_0} = \frac{T^2}{(1-R)^2 + 4R} = \frac{T^2}{(1+R)^2}$$  \hspace{1cm} (2.22)

The contrast factor \( C \) is defined as

$$C = \frac{I_{MAX}}{I_{MIN}} = \left(\frac{1+R}{1-R}\right)^2 = 1 + F$$  \hspace{1cm} (2.23)

Near a maximum the points where \( I_T = \frac{1}{2} I_{MAX} \) are characterized by a phase

$$\delta = 2m\pi \pm \frac{\epsilon}{2}$$  \hspace{1cm} (2.24)

so that \( \epsilon \) is the full width at half maximum (FWHM) expressed as a phase. Using this definition in [2.15] we obtain

$$\frac{1}{1+F\sqrt{\frac{\epsilon}{2}}} = \frac{1}{2}$$
$$\sin \frac{\epsilon}{4} \simeq \frac{\epsilon}{4}$$

$$F\frac{\epsilon^2}{16} = 1 \Rightarrow \epsilon = \frac{4}{\sqrt{F}} = 2\frac{1-R}{\sqrt{R}}$$  \hspace{1cm} (2.25)

If we compare this quantity to the \( 2\pi \) maxima separation in phase we can define the reflecting finesse, which is a key parameter to characterize a Fabry-Pérot

$$\mathcal{F}_R = \frac{2\pi}{\epsilon} = \frac{\pi\sqrt{F}}{2} = \frac{\pi\sqrt{R}}{1-R}$$  \hspace{1cm} (2.26)

If we now consider the bright rings of maximum intensity, it is possible to calculate the diameter starting from [2.19] and taking into account even \( \delta \)

$$m = \frac{2n'd}{\lambda_0} \cos \theta' + \frac{\delta_r}{2\pi}$$  \hspace{1cm} (2.27)
Using an approximation for small angles
\[ \cos \theta' \simeq 1 - \frac{\theta'^2}{2} = 1 - \left( \frac{n'}{n} \right)^2 \frac{\theta'^2}{2} \]  
(2.28)
for a normal incident wave we have
\[ m_0 = \frac{2n'd}{\lambda_0} + \frac{\delta_r}{2\pi} = m_1 + e \]  
(2.29)
where \( m_1 \) is the integer part of the order \( m_0 \) and \( e \) is the fractional part of it. Then we have

\[ m = \frac{2n'd}{\lambda_0} \left( 1 - \left( \frac{n'}{n} \right)^2 \frac{\theta'^2}{2} \right) + \frac{\delta_r}{2\pi} \]
\[ \theta'^2 = \frac{1}{n} \sqrt{\frac{n'\lambda_0}{d}} \sqrt{\frac{2n'd}{\lambda_0} - m + \frac{\delta_r}{2\pi}} = \]
\[ \frac{1}{n} \sqrt{\frac{n'\lambda_0}{d}} \sqrt{m_1 - m + e} \]
if we now redefine the integer part as \( m_1 - m = p - 1 \) we obtain the angle for the \( p \)th order
\[ \theta_p = \frac{1}{n} \sqrt{\frac{n'\lambda_0}{d}} \sqrt{p - 1 + e} \]  
(2.30)
and given the focal ratio \( f \) for the focal lens, the diameter of the bright ring is
\[ D_p^2 = (2f\theta_p)^2 = \frac{4n'\lambda_0f^2}{n^2d}(p - 1 + e) \]  
(2.31)
The Fabry-Pérot as a Filter: Resolving Power, Full Width at Half Maximum, Free Spectral Range

If we now relax the monochromatic hypothesis we can analyse the Fabry-Pérot interferometer as an interference filter. Figure 2.4 shows the behavior of the instrument as a function of wavelength. The instrument transparency has several peaks, resembling a comb. The transmission profile depends on the value of the reflectivity $R$, as it has been computed in 2.11.

![Figure 2.4: Interference maxima and intensity profile for different values of R](image)

There are some key parameters that are useful to be defined for such a filter. We start from the resolving power, which is the capability to detect two near wavelengths; in other words it is the spectral resolution of the instrument with which it is possible to compare two different spectroscopic instruments. We start defining the two wavelengths as $\lambda_0 \pm \frac{1}{2} \Delta \lambda_0$ and the resolving power as

$$RP = \frac{\lambda_0}{\Delta \lambda_0}$$

(2.32)
In this case on the focal plane there is the superposition of two fringe systems. We adopt the Taylor criterion which states that the two components are still resolved if the distance between the maxima is such that the curves touch at half maximum. In this way the sum of the intensities at the saddle is equal to the maximum intensity for a single component. If we translate the difference in wavelength between the two components in a difference in phase $\epsilon$ we have

$$I_T = \frac{I_0}{1 + F \sin^2 \frac{\Delta \lambda}{2}} + \frac{I_0}{1 + F \sin^2 \frac{\Delta \lambda}{2}} = I_0$$  \hspace{1cm} (2.33)$$

which is analogous to the calculation we adopted to obtain the FWHM \text{2.25}. So we obtain that the $\Delta \lambda_0$ for the Taylor criterion is equal to the FWHM expressed as a wavelength. If we now differentiate \text{2.34}

$$|\Delta \delta| = \frac{4\pi n'd \cos \theta'}{\lambda_0^2} \Delta \lambda_0 = 2\pi m \Delta \lambda_0 = \frac{\Delta \lambda_0}{\lambda_0}$$  \hspace{1cm} (2.34)$$

Now using \text{2.25} and using $|\Delta \delta| = \epsilon$

$$2\pi m \frac{\Delta \lambda_0}{\lambda_0} = \frac{4}{\sqrt{F}}$$

$$\frac{\lambda_0}{\Delta \lambda_0} = \frac{m\pi}{2\sqrt{F}} = F_R m$$  \hspace{1cm} (2.35)$$

for $\theta \approx 0$ we have $m \approx \frac{2n'd}{\lambda_0}$ and so

$$\frac{\lambda_0}{\Delta \lambda_0} = \frac{2n'd F_R}{2n'd \cos \theta'} = \frac{\lambda_0^2}{F_R}$$  \hspace{1cm} (2.36)$$

$$FWHM = \Delta \lambda_0 (FWHM) = \frac{\lambda_0}{F_R m} = \frac{\lambda_0^2}{F_R \cdot 2n'd \cos \theta'}$$  \hspace{1cm} (2.37)$$
As a note we include here the FWHM in case of a generic \( \delta_r \) which has an additional term [Bor99]

\[
FWHM = \frac{\lambda_0}{F_R m - \frac{1}{2\pi} \left[ \frac{d}{d\lambda_0} (\delta_r, \lambda_0) \right]_{\lambda_0}}
\]

(2.38)

Another key parameter is the free spectral range (FSR), which is the difference in wavelength between two maxima in the transmission profile of the filter. In order to compute it we set

\[
|\Delta \delta| = 2\pi
\]

(2.39)

that we have seen previously is the phase difference between two maxima. So the FSR is

\[
FSR = \Delta \lambda_0 (FSR) = \frac{\lambda_0^2}{2n'd \cos \theta'} = \frac{\lambda_0}{m}
\]

(2.40)

and the relation between FSR and FWHM is

\[
FSR = F_R (FWHM)
\]

(2.41)

It is clear from this equation that the reflecting finesse \( F_R \) and the interference order \( m \) are the parameters to be carefully chosen to define the characteristics of the Fabry-Pérot. The order \( m \) (2.19), once defined the working wavelength, depends on the refracting index, the angle of incidence and the spacing. The angle \( \theta \) is usually set as much as possible near zero in order to maximize the order, which leaves us with two possible choices to change \( m \): either vary the refracting index \( n' \) or the spacing \( d \). The free spectral range, once set the wavelength and the order \( m \), is then fixed by equation 2.40. The reflecting finesse depends only on the reflectivity \( R \) and is set choosing a suitable multilayer dielectric coating. The FWHM is then \( F_R \) times smaller than the FSR 2.41.

If we think about an interferometer that can vary the position of the peak transmitted light over wavelengths, it is clear that the FSR is the maximum distance in wavelength of the instrument if we want to scan a certain region of a spectrum with a single peak. The FWHM is instead the key parameter to understand the spectral resolution. Combined, they describe the spectral behavior of a scanning Fabry-Pérot. In order to match the required standard for the instrument \( n', d \) and \( R \) must be carefully chosen.

### 2.2 The Real Fabry-Pérot

Till now, we have set the theory valid for an ideal interferometer made up by two perfectly plane and parallel, partially reflecting, plates. In this section we introduce non-ideal effects in order to describe a real Fabry-Pérot. Scanning filter systems and optical layouts are also described.
Effective Finesse

Key issues for a plane parallel interferometer are the defects of the plates, a non perfect parallelism and the effects of a non perfectly collimated beam. They cause a broadening of the spectral profile which can be taken into account as another term of finesse. We can model the effect of a non planar plate using the spherical defect finesse $F_{DS}$, where $\delta_{DS}$ is the peak to valley value of deviation from the plane surface.

$$F_{DS} = \frac{\lambda_0}{2\delta_{DS}} = \frac{K_S}{2}$$ (2.42)

Aside from systematic surface defects, a surface noise is always present after the plate has been polished. It can be described with the root mean square (RMS) of the difference between the measured and the ideal surface. It is called $\delta_{DG}$, where the G stands for Gaussian as the remaining noise, after eliminating all systematic, is Gaussian. The Gaussian defect finesse is then

$$F_{DG} = \frac{\lambda_0}{4.7\delta_{DG}} = \frac{K_G}{4.7}$$ (2.43)

Another problem is related to the fact that the internal gap of the interferometer can be wedged. In this case the nominal gap distance $d$ is a mean of the value over the aperture of the instrument, since $d$ vary linearly over the diameter of the etalon. The parallelism defect finesse $F_{DP}$ take into account effects of a not parallel couple of plates. $\delta_{DP}$ is the spatial value corresponding to the difference between the maximum and minum $d$.

$$F_{DP} = \frac{\lambda_0}{\sqrt{3}\delta_{DP}} = \frac{K_P}{\sqrt{3}}$$ (2.44)

Another strong hypothesis made in the description of the ideal Fabry-Pérot is the planarity of the incident wave. If the incident beam has a certain amount of divergence this results in a different angle of incidence for the outer rays of the beam, broadening the transmission profile. Given the solid angle of the beam $\Omega$ or the divergence angle of the beam $\theta_{DIV}$, the divergence finesse is then defined as

$$F_{DIV} = \frac{\lambda_0}{d\theta_{DIV}^2} = \frac{2\pi}{m\Omega}$$ (2.45)

It is also called the aperture finesse, since the aperture of the instrument limits range of possible angles of the diverging beam.

All previous definitions of finesse are now included in an effective finesse $F_E$ which now describes a real interferometer.

$$\frac{1}{F_E^2} = \frac{1}{F_R^2} + \frac{1}{F_{DS}^2} + \frac{1}{F_{DG}^2} + \frac{1}{F_{DP}^2} + \frac{1}{F_{DIV}^2}$$ (2.46)
This new quantity has to be used instead of the reflective finesse in all previous formulas for the ideal Fabry-Pérot in order to describe a real interferometer. If we go back to equations 2.37 and 2.40, it is clear that the spectral profile is broadened by an effective finesse lower than the ideal reflecting finesse, increasing the FWHM, while the FSR is left unchanged.

The transmitted intensity for the real case can be now computed using the effective finesse. Equation 2.11 in this way become

\[ I_T = I_0 \left( 1 - \frac{A}{1 - R} \right)^2 \frac{1}{1 + \left( \frac{2\mathcal{F}_E}{\pi} \right)^2 \sin^2 \frac{\Delta}{2}} \]  

(2.48)

Broadening of the transmission profile and consequent decrease in spectral resolution is not the only effect. There is also an additional reduction in the maximum transmission intensity, so that

\[ I_{MAX} \approx \left( 1 - \frac{A}{1 - R} \right)^2 \left[ 1 - \frac{1 + R}{2} \left( 1 - \frac{\mathcal{F}_E}{\mathcal{F}_R} \right) \right] \]  

(2.49)

**Prefilters**

A Fabry-Pérot interferometer is a good spectral filter with a quite high spectral resolution, given the appropriate construction parameters. As it is based on interferometry we have seen that its spectral response has not a single peak of transparency. It can be defined as a spectral comb filter with a peak for every order of interference. As we are interested in a filter with a single transparency peak, able to select a very narrow region of the electromagnetic spectrum, a Fabry-Pérot has to be combined with another band-pass filter, able to select a single order. This piece of the instrument is called a prefilter and its passband has to be carefully chosen to match the Fabry-Pérot free spectral range and the general usage of the instrument. A scanning Fabry-Pérot is designed so that its parameters can meet the demand for a certain spectral region of interest. This region is smaller than the free spectral range so that a single order peak can scan the region without having a second peak entering the region in the meanwhile. An ideal prefilter will have a 100% transparency in the spectral region of interest and zero elsewhere. Low resolving power filters are usually used as prefilters. Given a certain transparency profile for the prefilter, the instrument spectral profile will be the product of Fabry-Pérot and prefilter transparency functions. It is important to use an image quality prefilter with high transparency; otherwise, this could result in a lack of performance of the entire instrument.

If the Fabry-Pérot is used in a multi-line instrument investigating different zone of the spectrum, multiple prefilters are needed. In this case they are usually mounted on a filter wheel and inserted once at a time in the beam path.
Single Interferometer Optical Layouts

There are two main optical layouts used in instrument involving Fabry-Pérot: Classical Mount (CM) and Telecentric Mount. They are extensively investigated in [RCR10].

In TM the focal plane virtually coincides with the interferometer plates. Generally, however, it is not possible to install the interferometer in the primary focus of the telescope so an optical relay system is used. This system is composed of a series of lenses that transfer the focal plane of the telescope onto the interferometer plates. The first one of these lenses forms the image of the telescope entrance pupil and removes the solar image to infinity, and the second one forms the solar image and removes the pupil to infinity. In this optical setup, each image point is the vertex of a cone of rays, where each ray direction biunivocally corresponds to a point on the pupil. If we consider that the Fabry-Pérot spectral transmission varies according to the angle of incidence, the result is that it superimposes the well-known ring pattern on the pupil image, the aspect of which depends on the assumed working wavelength and f-number. In the case of the TM, the systematic imaging degradation can be calculated and largely controlled in the design phase by acting on the optics and on the interferometer parameters, while in CM the spectroscopical and the imaging effects due to the plate defects can be evaluated only when the cavity errors and their spatial distribution on the interferometer area are known.

The so-called classic mount may be viewed schematically as placing an enlarged interferometer in front of the entrance pupil of the telescope, which may be considered for the sake of clarity as a single lens having the diameter of the entrance pupil and the effective focal length of the real telescope. The phase shift affecting rays not parallel to the optical axis introduces a phase factor that only depends on the focal plane coordinates and is therefore canceled when evaluating the intensity. If we add a narrow band filter to our system, with a bandwidth less than one FSR, we would observe a transmission ring system superimposed on the image of the sky, as predicted by the FPI theory. The peak of the spectral Airy function depends on the pixel position on the focal plane. We are therefore in the presence of a spectral shift on the image plane, which must be considered in the data evaluation process.

For a given telescope aperture, the achievable field-of-view depends on the FPI useful area and the f-number of the incident beam. In the case of the CM, the f-number is limited by the tradeoff with the maximum wavelength shift that can be tolerated on the focal plane, while in TM, the f-number is dictated by with the minimum allowed optical quality. On the other hand, large-scale plate gap errors limit the FPI useful area in the case of the CM, in a tradeoff with minimum admitted optical quality. In TM, the same tradeoff in useful area is made with the maximum local detuning that can be tolerated on the focal plane.

Multiple Fabry-Pérot Layouts

Two or three Fabry-Pérot in series may be used to select a single transmission peak, rather than using a prefilter. This is possible choosing the two appropriate different values of FSR
for the two Fabry-Pérot interferometers forming the instrument and matching a maximum for each of them. Combining multiple Fabry-Pérot in series can produce higher spectral resolution and free spectral range. This approach has been widely used in Solar Physics, where very high spectral resolution \((RP \sim 100\,000 \div 300\,000)\) is required. However the presence of multiple interferometers in the optical path also produces spurious spectral effects due to ghost reflections occurring between the two Fabry-Pérot. Proper design of the geometry of the instrument can minimize these effects.

**Instrument Characterization and Calibration**

Using the method described in [RC08a] for the characterization of a Fabry-Perot interferometer, it is possible to measure both the spatial distribution of the large-scale plate errors and magnitude of the randomly distributed small-scale errors down to the level of the unresolved microroughness. From these measurements it is also possible to provide estimates of the coating reflectivity and absorption. The technique involves spatially resolved measurements of the transmission profiles over an area illuminated by a stabilized He-Ne laser. The laser must have the width of the emission profile much narrower than the transmission profiles we are attempting to measure. The laser operates at a fixed wavelength and the spectral scanning is performed by changing the wavelength position of the interferometer transmission profile through incremental increases in the plate spacing. In this way the interferometer profile is sequentially sampled from longer to shorter wavelengths.

Tests are conducted in collimated configuration. The laser beam passes through a pinhole and a collimating lens; a shear plate interferometer is used to check the beam divergence. A series of subsequent lenses reduce the beam size in order to fit the camera dimensions. A pixel by pixel analysis is performed, studying the FWHM of the transmitted light. The mean shape of the observed pixel profiles can be approximated with that of an ideal Fabry-Pérot broadened by a Gaussian distribution of unresolved microroughness. In this scenario, the mean pixel profile would be statistically well represented by a Voigt function, resulting from the convolution of an Airy function \(T\) and a Gaussian distribution \(d_G\) of microroughness errors, defined by a standard deviation \(\sigma_\lambda\):

\[
T' = T(R) \delta_G(\sigma_\lambda) \tag{2.50}
\]

For each combination of \(R\) and \(\sigma_\lambda\), the resulting profile \(T'\) will have a unique combination of FWHM and width ratio.

If the angle between the planes fitting the inner surfaces of the two interferometer plates is different from zero, then the interferometer is said to be non-parallel. The resulting gradient in plate separations will introduce a corresponding trend in the profile shifts observed across the aperture of the Fabry-Pérot.
2.3 Fabry-Pérot Applications

Solar Physics Applications

High-cadence and high-resolution spectro-polarimetric observations of the lower solar atmosphere are a key tool to investigate highly dynamic phenomena present in these layers of the atmosphere of our star. A fast camera system and a panoramic and high-transparent spectrometer allow to obtain a suitable cadence to study high-frequency oscillations and fast-moving plasma present in the solar photosphere and chromosphere. A high spectral resolving power ($R \geq 200,000$) is required to properly analyze narrow photospheric lines and a high temporal resolution (several frames per second) is necessary to investigate highly dynamic solar phenomena. The exposure time must be sufficiently short to satisfy the Nyquist frequency associated with the analysis techniques required to exploit the acquired dataset. A sufficiently large field of view (FOV) is essential to easily study active regions and a suitably extended wavelength range, visible-NIR, is needed to offer a broad option among lines with different diagnostic power. Finally, a high wavelength stability (maximum drift 0.02 pm in 10 hours) is mandatory to provide a good reproducibility of the selected spectral points in long observing runs (e.g., oscillatory phenomena). To this purpose, the Fabry-Pérot interferometer seems to be a good candidate.

As an example we report requirements for chromosphere investigations from CRU+08. The chromosphere embodies the transition between the photosphere and the corona, two regions dominated by vastly different physical regimes. In particular, it is within the chromosphere that the plasma $\beta$, the ratio of plasma kinetic pressure to magnetic pressure, falls below unity, signaling a shift from hydrodynamic to magnetic forces as the dominant agent in the structuring of the atmosphere. […] Such fine structure represents a formidable challenge even to the most modern instrumentation, as its study requires high spectral resolution, necessary to resolve line profiles encoding large gradients or discontinuities, combined with extremely high temporal and spatial resolution. […] Among the chromospheric diagnostics accessible to ground-based observations, the Ca II H and K resonance lines have been used most extensively. […] In this framework, we introduce here new high resolution observations of the Ca II 854.2 nm line obtained in a variety of solar structures with the Interferometric BIdimensional Spectrometer, installed at the Dunn Solar Telescope of the US National Solar Observatory. […] IBIS is a high performance instrument that combines most of the advantages of a full spectroscopic analysis, usually obtained with single-slit spectrographs, with the high spatial resolution, high temporal cadence and large field of view typical of filter instruments. Such characteristics are necessary to obtain new insights into the structure and dynamics of the chromosphere. […] The stability and large throughput of the instrument, combined with the excellent performance of the high-order adaptive optics system available at the DST, make it possible to investigate the highly dynamic chromospheric environment while maintaining
excellent spatial and spectral resolution, despite the obvious drawback (common to all filter-based instruments) of a sequential spectral acquisition. A comparison of the average properties of the spectral line profiles and of the global dynamics over a quiet target area with earlier results, obtained with classical fixed-slit spectrographic techniques, demonstrates indeed that the spectral information provided by IBIS is fully reliable and achieves a quality on par to those of dispersion-based measurements.

The instrument used in CRU+08 is the Interferometric BIdimensional Spectrometer (IBIS) operated at the Dun Solar Telescope of Sacramento Peak observatory CBR+03. It essentially consists of two Fabry-Pérot interferometers, piezo-scanned and capacity servo-controlled, used in classic mount and in axial-mode, in series with a set of narrow-band interference filters. The instrument operate on a large field of view (8′′) and on a large wavelength range (580 ÷ 860 nm), with high spectral, spatial and temporal resolution CCR+06.

Figure 2.6: IBIS data example. From left to right: Fe I709.0 nm sample spectral points, continuum, line core

Other Astronomical Applications

Beyond the Sun, tunable filter can be applied to the study of many other astronomical objects. For a review of the topic we suggest the reading of Bla03, reporting here only a small lists of scientific targets

- Star forming galaxies surveys.
- Galaxy clusters.
- Quasar environments.
- Energetic gas in clusters
- Gravitational lensing.
- Quasar nebulae.
- Seyfert galaxies.
• Starburst galaxies.
• Disk-halo connections in spirals.
• Star formation in elliptical and spiral galaxies.
• Stellar populations in galaxies.
• Pulsar wind nebulae.
• Interstellar medium.
• Weather in brown dwarfs.
• Variable stars.
• Planets.
Chapter 3

Fabry-Pérot Prototype

We are realizing a prototype interferometer at the Solar Physics Laboratory of University of Rome Tor Vergata. We have chosen the instrument characteristics to match the required performance of a tunable interference filter for solar physics applications both for ground based and space use. The main goal is to produce an instrument suitable for the ADAHELI satellite mission. ADAHELI is a small-class low-budget satellite mission for the study of the solar photosphere and the chromosphere and for monitoring solar flare emission. A tunable, capacitance stabilized, couple of Fabry-Pérot interferometer with an adjustable optical cavity dimension has been proposed as the core of the narrow band channel of the satellite. The prototype is intended to be an important step towards the instrument realization.

![Prototype optomechanical design](image)

Figure 3.1: Prototype optomechanical design

We have designed the Fabry-Pérot in order to test the reliability of the proposed fine adjustment system, based on piezoelectric actuators used in a servo controlled closed loop.
This prototype shares similar optical and control system components with the final Fabry-Pérot version for space applications. As it is clear from the previous chapter, extreme flatness and excellent optical quality of the mirrors are necessary to obtain a filter with a high resolving power.

Therefore we have designed the prototype to have the lowest mechanical and thermal stresses on the optical plates. The main function of the optomechanical system is to allow one of the optical plates to move, varying the dimension of the optical cavity between the coated surfaces (known as the Optical Path Difference or OPD), obtaining a spectral shift of the instrument passband. At the same time, it provides the mechanical constraints which permit the correction of the tilt angle between the two optical surfaces.

The proposed control system for the test prototype allows two levels of adjustment, in order to extensively vary the resolving power and the free spectral range of the filter.

Micrometers and piezo actuators are both computer controlled. The control system is able to compensate possible mechanical misalignments in the test phase. The double adjustment requires a complex optomechanical structure which has been realized only for the test prototype.

The Fabry-Pérot etalon for space application will have only the fine adjustment, requiring a precise machining of the plates constraints. Therefore it will not allow for misalignment adjustment correctable with more than a small fraction of the total elongation of the piezoelectric actuator. Another important difference is that we have designed the laboratory prototype to support the gravity load. On the contrary the space model will not be subjected to gravity when in orbit. It will be conceived to resist gravity while on ground as well as to withstand the launch stresses.
3.1 The ADAHELI Mission

ADAHELI is a small-class low-budget satellite mission for the study of the solar photosphere and the chromosphere and for monitoring solar flare emission. ADAHELI’s design has completed its Phase-A feasibility study in December 2008, in the framework of ASI (Agenzia Spaziale Italiana) 2007 Small Missions Program. CGS SpA was leader industry and University of Rome Tor Vergata was leader scientific institution of the project. During its Nominal Mission (two plus one years) ADAHELI shall constantly point the Sun, except during maneuvers, eclipses or contingencies. The spacecraft radial velocity in the sunward direction, shall not exceed $\pm 4 \text{km/s}$, during 95% of the yearly orbit. The initial accuracy in pointing a selected Region Of Interest (ROI) must be a small fraction of the field of view, say $< 10 \text{arcsec}$, to get the ROI within the field of view of the high resolution ISODY telescope. The precision in tracking the ROI must be significantly better, i.e. $< 0.1 \text{arcsec}$ for the whole duration of the acquisition, to allow the planned high quality of the image series. This must be achieved by the combined action of the satellite Attitude and Orbit Control Subsystem (AOCS) and of the correlation tracker correction system inside the telescope. The satellite relative velocity with respect to the Sun center shall be known within 1 cm/s. These very challenging requirements, flow down constrained the design of the main instrument, ISODY. Further details on the mission and its requirements may be found in [ABB+10] [BVR+09] [BVR+08]. The satellite configuration is characterized by a prismatic bus with body fixed solar array and payloads mounted as shown in figure 3.3. The proposed configuration is compatible with the VEGA launcher.

![Figure 3.3: ADAHELI configuration](image)

ISODY [GCB10] is designed to obtain high resolution spatial, spectral, and temporal polarimetric images of the solar photosphere and chromosphere. The Focal Plane Assembly of
the ISODY instrument comprises two visible near-infrared science optical paths or channels: the Narrow Band (NB) and the Broad Band (BB) channels, as well as the Correlation Tracker (CRTR) channel. The optical path with the relative positions of the optical elements/units for the NB channel is shown in figure 3.4 and consist in 25 items and/or assemblies, as briefly described in this paragraph. A dichroic mirror (item DM on the figure) transmits part of the telescope beam towards the BB channel in the wavelength range 530-670 nm and reflects part of the beam to the NB channel in the range 850-860 nm. The principal optical path of the NB channel is formed by three folding mirrors (M4, M5 and M6) and three converging lenses (L1, L2 and L3), which successively collimate the solar and the pupil images. After L2, there are two Fabry-Pérot interferometers (FP1, FP2) used in axial-mode and in classic mount and, between them, a filter wheel (FW) carrying a hole, a dark slide and four interference filters.

Figure 3.4: The optical path and the relative positions of the optical elements/units of ISODIY Narrow Band channel.

All the optical instrumentation is mounted on an Optical Bench of honeycomb with sufficient stiffness to be self-supporting and maintain a good planarity on-ground and in-orbit. The envelope of the complete Focal Plane Assembly is 1600 x 900 x 280 mm. The instrumentation is enclosed in a box of dimensions 1600 x 900 x 200 mm. A Classical Mount (CM) has been adopted for the system. From the spectroscopic point of view this mount, with respect to the telecentric one, has the advantage of a transparency profile with the same shape at all the points of the final image. Moreover, its systematic blue-shift is not difficult to correct, allowing use of larger incidence angles than the telecentric mounting, which needs, on the contrary, small relative apertures to achieve good image quality and spectral resolution. This implies that the CM generally allows a larger FOV.
3.2 Capacitance Stabilized Etalon Setup

The chosen type of Fabry-Pérot is a scanning optical cavity with a gap servo control system. The main idea of the prototype is an instrument capable of maintaining two partially reflecting mirrors at the required distance, parallel within the tolerances (see tab.3.2). Since the wavelength position of the filter transmission peak is determined by the gap dimension (eqn.2.19), this distance must be varied in order to scan a certain spectral range of interest. This distance must instead be maintained during the instrument acquisition time and then changed to reach the next wavelength. In addition, positioning repeatability must be guaranteed in order to obtain the same spectral points in subsequent measures. To achieve these goals we have used piezoelectric actuators and capacitive sensors. The combination of these two technologies in a servo controlled system allows to achieve absolute positioning with the necessary stability and repeatability ($\lambda/3000$ over one day or more [HRA84]).

![Figure 3.5: Prototype exploded](image)

We have designed the optomechanics of the laboratory prototype to house (see fig. 3.5): a pair of $2''$ (5.08 cm) partially reflecting mirrors, three micrometers, three piezoelectric actuators, three high sensitivity capacitive sensors. We have also designed an adapter to use the currently available $1''$ (2.54 cm) optical plates. The maximum allowed travel is 12 mm for micrometers and 15 $\mu$m for piezoelectric actuators. The high sensitivity capacitive sensors working distance is 50 $\mu$m. The control loop is managed by a dedicated controller, calibrated on the selected piezoelectric actuators and capacitive sensors.
<table>
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<th>Value</th>
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<tr>
<td>Refractive Index</td>
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<td>Mirror Absorption Coefficient</td>
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</tr>
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<td>Small Plate Defects</td>
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</tr>
<tr>
<td>Parallelism Defects</td>
<td>6 nm</td>
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</tbody>
</table>

Table 3.1: Fabry-Pérot Parameters

### 3.3 Optical Characteristics

We have set optical requirements for the plane partially reflecting mirrors (PRM) in $\lambda/100$ for the maximum deviation of the surface shape from the ideal plane and $R = 0.9$ in the range from 550 nm to 900 nm for the dielectric coating reflectivity (see transmittance value in 3.6).

Tor Vergata Solar Physics Laboratory has charged LightMachinery, a company specialized in high precision optical components, to produce a couple of $1''$ (25.4 mm) diameter mirrors. The plates are wedged with an angle of 30' to avoid unwanted additional reflections between the uncoated faces. The mirror thickness is 15 mm. Due to production issues, the requirements have not been met. A pair of $\lambda/60$ plates was instead provided and is being tested at the moment, while a new set with the required parameters is under production. The data about surface defects of these plates have been released and we have used them to improve the Fabry-Pérot model.
LightMachinery analysed the plates with a Zygo interferometer, measuring peak to valley and RMS surface defects. LightMachinery has performed the analysis first on a 10 mm diameter disk (40% of the area, see fig. 3.7) at the center of the plate, where the optical quality is better. Then they have measured the same quantities again on a 22 mm diameter disk (80% of the area, see fig. 3.10), which is the effective usable area of the plate since the rest of the disk is uncoated. The polishing process tends to be less accurate on the edge of the plate, resulting in a slightly concave shape of the optical surface. This can be treated in first approximation as a spherical aberration. The remaining surface noise can be treated as Gaussian.

Plate Intensity map, 2-D (fig. 3.7, 3.10) and 3-D surface error plots (fig. 3.9, 3.12), surface irregularities profile along a cutting line (fig. 3.8, 3.11) are shown, in subsequent figures, for one example plate for both the 10 mm and 22 mm diameter areas. Scales are reported as fraction of the the reference wavelength $\lambda_{REF} = 632.8$ nm. Figures are courtesy of LightMachinery. With respect to equations 2.42, 2.43 the plates are characterized by $\delta_{DS} = 10.8$ nm and $\delta_{DG} = 1.9$ nm.

We will use the bidimensional map of the surface inequalities to compute the best possible alignment between the pair of plates, minimizing the cumulative surface errors with the appropriate rotation around the optical axis.
Figure 3.7: 10 mm diameter. On the left the intensity map; the circle highlights the area corresponding to the image on the right, where 2-D defects map with the reference cutting line is shown.

Figure 3.8: 10 mm diameter. Surface defects along the cutting line.

Figure 3.9: 10 mm diameter. 3-D surface defects plot.
Figure 3.10: 20 mm diameter. On the left the intensity map; the circle highlights the area corresponding to the figure on the right, where 2-D defects map with the reference cutting line is shown.

Figure 3.11: 20 mm diameter. Surface defects along the cutting line.

Figure 3.12: 20 mm diameter. 3-D surface defects plot.
3.4 Mechanical Characteristics and Double Motion Control

The mechanical design of the test prototype is characterized by modular elements, and based on a $120^\circ$-symmetry. The resulting reference system for the movements is easily schematized within the control software and the mechanical elements are easy to produce with numeric control machines. The main aim of the optomechanical system is to allow the movement of the two optical surfaces that form the resonant cavity, keeping the plates parallel. In addition we have designed this prototype to decouple two different movements of the optical surfaces, in order to enable a coarse and fine adjustments of the cavity gap. In the laboratory configuration the holder has to compensate for gravity deformations, maintaining aligned along the optical axis the centers of the two mirrors.

Each optical surface is housed in a different component: one is fixed to a base plate, the other is housed in a mobile plate which rests on the base plate by the use of a ball-tip screw. The ball-tip screw is coupled with a V-groove in order to allow rotations and displacements parallel to the optical axis.

![Figure 3.13: Movable optical element support with the decoupling mechanism for coarse and fine adjustments](image)

We have given special attention to mechanical stresses to which mirrors are subjected due to the support constraint. In order to minimize these effects, we have designed special flexures (see in appendix the technical drawings) to join the optical element to the main metal ring used to support it in the proper position. Flexures are joined to the side of the optical element by means of a specific acrylic glue designed to fix together metal and glass. This type of mount is able to provide grip without stress on the object and to provide for damping any movement.
perpendicular to the optical axis. We have studied a dedicated tool to precisely assemble the optical surface to its three flexure devices (see fig. 3.13).

Decoupling of the coarse and fine adjustments is achieved by separating the mobile plate into two concentric rings. In this way the distance between the fixed plate and the movable one can be changed using two different kinds of actuators. Adjustments are performed by three micrometers and three piezoelectric actuators placed in a 120°-symmetry around the etalon.

Motorized micrometers act on the outer ring, the contact being preserved by the use of three preloaded springs in 120°-symmetry. They are used to set the approximate working distance and for planarity correction between the two optical surfaces. Since they can change the optical cavity size of millimeters, they are used to vary the free spectral range and the resolving power of the instrument.

The inner ring, which houses the mobile optical surface, is controlled by the piezoelectric actuators. They are used to vary the gap size within optomechanical specifications. Piezoelectric actuators are used to move the filter passband along the spectral region of interest. In this way the instrument is able to sample different spectral points in the working range. Absolute position and repeatability are guaranteed by the high sensitivity capacitive sensors placed in a 120°-symmetry on the backside of the piezoelectric actuators. They work together with the piezoelectric actuators avoiding the hysteresis of the actuators response. The outer ring is connected to the inner ring by three V-shaped flexures which also provide the contact between piezo-actuators and the inner ring.

The piezoelectric actuators are kept in place by the use of a third support plate, attached to the outer ring of the mobile plate. Thus, a micrometer displacement moves both the mobile and the support plates, while a piezoelectric actuator displacement moves the inner ring of the mobile plate only. In order to realize kinematic couplings, both micrometers and piezoelectric actuators are equipped with ball-tip ends acting on a V-groove.

The V-grooves are carved out from the metal plate. We have preferred this solution over the assembly of dedicated cylinders to form the V-groove for simplicity and to limit the pieces to be mounted. The ball tips could be coupled to the metal plate surface also in other ways obtaining the same kind of constraint. The other most common type of kinematic coupling involves a cone, V-groove and a plane as contact surfaces. Again, we have chosen the three V-grooves for their ease implementation. Both the ball-tip ends and the V-grooves contact surfaces will be made in stainless steel to reduce hysteresis in the contact area and providing an almost-Hertzian contact (mechanical theory for contact between two elastic bodies with curved surfaces).
Although motorized micrometers are used for coarse movements (up to 20 mm), accuracy under 50 μm is however required. We have chosen a set of three Thorlabs DC Servo Motor Actuators Z812B. They are computer operated using a dedicated software developed in LabView for the prototype. The model has been chosen for the high step resolution, 29 nm, provided by the included Hall Effect encoder. The backlash under 8 μm and the bidirectional repeatability under 1.5 μm provide the sufficient position precision required for the coarse adjustment. The smallest optical plate tilt angle correctable with this subsystem, given the distance of the fulcrum from the optical axis and minimum step achievable, is $29 \text{ nm}/60 \text{ mm} \simeq 0.1 \text{ arcsec}$. Given an axial load capacity of 82 N, the micrometers can be preloaded with springs with sufficiently high tension load. We dimensioned the latter to support the movable plate for gravity, together with the ball-tip screw under the same plate. Other features of the micrometer are shown in the table C.1.

---

DC Servo Motor Micrometers

Figure 3.14: Two kind of kinematic coupling
Figure 3.15: Thorlabs Z812B Servo Motor as it has been tested on the optical bench

Figure 3.16: PICMA P-887.51 actuator and its case. High voltage wire is visible
Piezoelectric Actuator and Capacitive Sensor

Fine adjustments of the movable optical plate is achieved using piezoelectric actuators. Piezo actuators can perform sub-nanometer moves at high frequencies because they derive their motion from solid-state crystalline effects. They have no rotating or sliding parts to cause friction and dissipate virtually no power in static operation.

We have chosen the PICMA P-887.51 actuator (see figure 3.16) manufactured by Physik Instrumente (PI). It has a nominal displacement of 15 $\mu$m under an applied voltage of 100 V and has the possibility to reach nanometric precision. It is operated using an analog driving signal coming from a dedicated PI controller.

The latter can be summarized as a high stable voltage amplifier able to multiply by ten the input signal. It accepts a $-2 \div 12$ V range input voltage, outputting a $-20 \div 120$ V signal in response. The system is computer operated via a Digital to Analog Converter (DAC) manufactured by National Instruments (NI). The DAC model is a NI 6259 with 4 analog output lines and 32 analog output lines. It has a 16-bit resolution, resulting in 0.15 $mV$ minimum output voltage step. After the signal processing by the PI controller this results in a 0.44 $nm$ minimum step of the piezo actuator. Other parameters of piezo and controllers can be found in C.2 C.3.

Figure 3.17: Piezoelectric actuator hysteresis cycle and linearization scheme for a 100 $\mu$m displacement PICMA model
Unfortunately, the piezoelectric actuator response to the signal is not linear and follows an hysteresis cycle. This issue can be overcome using a closed loop control system which involves an high precision distance sensor. Using the distance, correct high tension value is computed in order to have linear response for the elongation value. In this case, we have used a capacitive sensor with a static resolution $< 1\ \mu m$. We can schematize it as a parallel plate condenser, whose capacity is measured to determine the gap. One plate is the extremity of the sensor itself, while the other is the target object. This latter surface has to have a machined surface with defects $< 1\ \mu m$ RMS, requiring a polishing with a lapping machine. We can measure the position and the distance changes of the target with very high precision through a capacitive bridge [Pie]. Using this information, the PI controller is able to operate a servo correction and linearize the response. The capacitive sensor has a working range centered at a distance of $50\ \mu m$ from the target. For this reason it must be positioned at the correct working distance each time the optical cavity gap is modified using the micrometers to change the FSR. We have designed a dedicated case for this purpose. See also table [C.2](#).

The PI piezo actuator has been proven to be able to operate in low pressure and low temperature compatible with space environments ($2\ K$ and $0.5\ bar$) [BPP]. Even if this prototype is meant to operate in a laboratory, we have chosen space suitable components to be tested and to prove reliability. We have enclosed the Piezo in a dedicated case with a spring-like design to ensure a small preload and to avoid shear stresses (see the technical drawing Scatola Piezo in appendix). The system configuration requires three piezo to achieve a correct positioning of the movable optical plate and to perform the spectral scanning.

As an example, changes of the optical cavity of $10\ nm$ at a time are necessary to sample the H-alpha line 35 times with a distance of $8.5\ pm$ from one point to the other in a working range of $0.3\ nm$ centered on the line. During the initial test phase we will use an interference prefilter with a bandwidth of $0.07\ nm$. Each piezo actuator has a corresponding capacitive sensor that measure the inner ring shift as in the scheme [3.18](#). Since the measured gap is not directly the optical cavity, extreme stiffness of the system is required, resulting in a prototype almost made only of steel.
Figure 3.18: Piezoelectric actuator and capacitive sensor scheme. When the piezo actuator push on the left side of the inner steel plate, capacitive gap on the right shrinks. The sensor read this information and through servo control we ensure that the variation is linear with driving tension variations.
3.5 Apparatus Requirements and Expected Apparatus Performance

We have already discussed the definition of the optical requirements. Optical parameters constrain the distance between the cavity surfaces and the tolerances on their parallelism, specifying the minimum displacement that has to be controlled by the fine adjustment. Operating requirements concern the survival of the components and their correct functioning in the operating environment. The test ground-based Fabry-Pérot will be subject to gravity loads; the space Fabry-Pérot interferometer instead will undergo temperature cycle/shock, thermal/vacuum and vibration/shock and severe accelerations during the satellite launch, and will operate in vacuum. In the case of the prototype interferometer, optical requirements set the operating distance between the etalon surfaces to $\sim 1.0 \text{ mm}$ (see 3.6). The main operating requirements concern the minimization of misalignments of the optical surfaces due to gravity load, and minimization of hysteresis at contact areas.

FEM simulations have been performed to study different materials, flexures shapes and retaining springs rigidities. Optical requirements set the maximum displacement allowed at 50 nm along the optical axis \([BCG+11]\). The material selected for the optomechanical hardware is stainless steel. The main features that we have considered were:

- Material cost and availability.
- Elastic modulus.
- Surface hardness.
- Electrical conductivity.
- Coupling with off-the-shelf components (screws, springs).

To study the support performances, we performed analyses in two loading conditions: gravity load and actuator displacement. Given the interferometer layout, gravity acts in the direction normal to the base plate, generating unwanted distortion in every operating condition. We have to avoid unpredicted deflections of the fixed optical surface, since we cannot measure for its position during the observations.

Optomechanical hardware rigidity resulted as extremely important in the test prototype design. All the components should have a rigid body behavior during the adjustment operations, because the capacitive sensors measurement is taken on the inner ring of the mobile plate (not on the mobile optical surface directly). At the same time, another important point is the correct design of the flexures connecting the inner and outer rings of the mobile plate. The aim of these flexures is double:

- To keep the inner ring in place against the gravity action.
To create a weak constraint to keep in contact piezo actuator with the inner ring, avoiding to prevent the fine movement.

We studied typical and maximum displacements conditions, both in frequency scan and parallelism adjustments. Results showed that the effect of gravity load on the etalon surfaces is acceptable. We performed Finite Element analysis (FEM) to compute static deformations due to gravity, or gravity and actuators. Gravity is on the y-axis, z is along the optical axis. In figure 3.19 result from the gravity load only is shown. Maximum overall displacement is 167 nm from the support plate. Fixed optical surface has a displacement of 13.2 nm in the y-direction and of 8.39 nm in the z-direction. Mobile optical surface instead has a 93.5 nm and 37.4 nm of displacement respectively.

Figure 3.19: FEM analysis: gravity load. Gravity is on the y-axis, z is along the optical axis

We studied other two cases, applying different elongations to the actuators. In the first case (fig 3.20) micrometers elongation is used to simulate a substantial tilt-angle correction. Elongation values for the three micrometers are 50 µm, 100 µm and 25 µm. Last case was an asymmetric elongation of piezo actuators of 7 µm, 5 µm and 3 µm (fig. 3.21). In both cases deviations from rigid body behavior are negligible, below nanometric scale.
Figure 3.20: FEM analysis: micrometers asymmetric elongation + gravity. Gravity is on the y-axis, z is along the optical axis

Figure 3.21: FEM analysis: piezo actuators asymmetric elongation + gravity. Gravity is on the y-axis, z is along the optical axis
Changes in thickness of the inner ring, due to temperature variations, are sensed by the electronic control which reacts by changing the OPD. This implies that the position in wavelength of the profile of transparency, is sensitive to temperature. If \( K = 17 \times 10^{-6} \, K^{-1} \) is the linear thermal expansion coefficient of the ring, we have:

\[
\frac{\Delta \lambda}{\lambda} = \frac{\Delta T}{T} = K \tag{3.1}
\]

And this results in a spurious Doppler signal

\[
\frac{\Delta \lambda}{\lambda} = \frac{v}{c} = K \tag{3.2}
\]

\[ v = K \frac{c}{5.1} \, km s^{-1} \, ^{\circ}C^{-1} \]

This means that we have to kept constant the temperature of the interferometer within \( \pm 0.01 \, ^{\circ}C \) to have a maximum drift of the instrumental profile of \( \pm 25 \, ms^{-1} \). Typical spectral drift allowed are of the order of \( < 10 \, m/s \) in 10 hours [CBCE00]. The space prototype will have a spectral stability of this order. Additionally we have to take into account the variation of the permittivity \( \epsilon \) with humidity, which affects the capacitive sensor measures. The variation is of the order \( \Delta \epsilon \simeq 2 \times 10^{-6} \) for a variation of 1% in humidity of the air. It corresponds to a spurious variation of the measured distance of 100\,nm for a capacitive sensor gap of 50\,\mu m [HRA84]. A method to reduce temperature, pressure and humidity effects consists in including a reference capacitive sensor, which measures the air variations only.

The index of refraction changes with humidity too. It is affected even by temperature and pressure, causing other spectral drifts. A change of 1% in relative humidity will cause a change in optical spacing of \( \frac{\lambda}{5 \times 10^3} \) per mm of plate separation \((\lambda = 500\,nm)\). The effect scales linearly with plate separation. The dependence of refractive index on temperature will cause changes in optical spacing of \( \frac{\lambda}{500} \, K^{-1} \) per mm of plate separation and with pressure \( \frac{\lambda}{120} \, kPa^{-1} \) per mm of plate separation \((\lambda = 500\,nm)\). We can eliminate these effects by enclosing the etalon in a sealed chamber. At constant volume, the temperature coefficient of refractive index is substantially reduced, giving an overall stability of \( \frac{\lambda}{2 \times 10^{7}} \, K^{-1} \) per mm of plate separation.

### 3.6 Fabry-Pérot Simulation

During the thesis work, I have developed a software model to simulate the performance of the prototype. The IDL code can be found in appendix B.1. I have used an effective finesse as it has been described in equations 2.47 and 2.48 to compute the real response of the Fabry-Pérot respect to the ideal one. The parameters used in the simulation have been derived from technical notes of the various parts of the prototype described in this chapter. They are listed in table 3.2.
I have simulated three Fabry-Pérot, with three different OPD. The values taken into account are 0.3 \( mm \), 1.0 \( mm \) and 3.0 \( mm \). A comparison table between the real and the ideal case parameters obtained from the simulation is shown in table 3.6. The simulation aim is to decide what value of the OPD makes the instrument more suitable to scan the H-alpha line, taking into account the available prefilter too. The latter is schematized with a Gaussian profile centered on the H-alpha line, with a peak transparency of 80%. I have considered the known bandwidth of 0.07 \( nm \) the zone of the Gaussian function where this is up the value of \( \frac{1}{\sqrt{2}} \) of the maximum, i.e. \( BW = 2\sigma\sqrt{\ln(2)} \) giving a \( \sigma = 0.042 \) \( nm \). Subsequent figures 3.22, 3.23 and 3.24 show the transmission profile for the Fabry-Pérot with the three different OPD, both in the ideal and real case. The broadening of the transmission profile and the lowering in transparency for the real case is evident. The FSR is bigger for a smaller OPD, as expected. Spectrum region is near the H-alpha line.

Figure 3.22: Fabry-Pérot FSR analysis: ideal case dotted, real case dashed. Optical Cavity 0.3 \( mm \)
<table>
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<th>Optical Gap 0.3 mm Simulation</th>
<th>Optical Gap 1.0 mm Simulation</th>
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<td><strong>Ideal Parameters</strong></td>
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<td>FSR</td>
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Table 3.2: Fabry-Pérot Simulation Results
Figure 3.23: Fabry-Pérot FSR analysis: ideal case dotted, real case dashed. Optical Cavity 1.0 mm

Figure 3.24: Fabry-Pérot FSR analysis: ideal case dotted, real case dashed. Optical Cavity 3.0 mm
Subsequent figures show the product of the prefilter profile and the Fabry-Pérot profile for the same three optical gaps. Note that in this case relative intensity on the vertical axis is on a logarithmic scale. The spectrum region is centered on the H-alpha line at 656.28 nm.

Figure 3.25: Dot-dashed: prefilter profile. Dotted: prefilter and Fabry-Pérot profiles product. Optical Cavity 0.3 mm

Figure 3.26: Dot-dashed: prefilter profile. Dotted: prefilter and Fabry-Pérot profiles product. Optical Cavity 1.0 mm
It is evident that the presence of multiple peaks of the Fabry-Pérot in the spectral region selected by the prefilter is unwanted as it results in a non-trivial sum of different spectral features. For this reason the case with an optical gap of 3.0 \textit{mm} is rejected. In a trade-off between the FSR and FWHM set by the optical gap, and using equation 2.41, the 1.0 \textit{mm} value is accepted for the tests. In figure 3.28 it is also shown an image of the H-alpha zone of the solar spectrum with the real peaks of the instrument superimposed. The prefilter profile is also shown, together with the product with the Fabry-Pérot transparency.
Figure 3.28: Continue and dotted, in the upper zone of the image: H-alpha zone of the solar spectrum. Dot-dashed: prefilter profile. Dotted: real Fabry-Pérot comb peaks. Red dashed: prefilter and Fabry-Pérot profiles product. Optical Cavity 1.0 mm
3.7 Control System Software

The control system involves the use of a program (see appendix B.3) which inputs the scan sequence during the observation, and the use of the loop controller to manage the fine adjustment by the piezoelectric actuators based on the capacitive sensors measurements. I have developed a LabView program to control the motorized micrometer using Thorlabs DLL. It is possible to control the motion in absolute value using home position as reference or to advance relatively to the last position. It is possible to set a maximum and minimum elongation too. This will be very useful to avoid a clash between the two plates and to avoid unwanted frictions. The program is currently able to control one micrometer at a time. An implementation of a system capable to control all three micrometers and to correct for tip-tilt misalignment is under development. It will be necessary to perform a change in the reference system in order to transform the 120°-symmetry push to a perpendicular tip-tilt correction. The coordinate transformation of the elongation $\Delta R$ of the A, B and C micrometers in the elongation on the X, Y and Z axes is of the form

$$
\begin{pmatrix}
\Delta R_A \\
\Delta R_B \\
\Delta R_C
\end{pmatrix} =
\begin{pmatrix}
0 & -1 & -1 \\
-1 & 0 & -1 \\
+1 & 0 & -1
\end{pmatrix}
\begin{pmatrix}
\Delta R_X \\
\Delta R_Y \\
\Delta R_Z
\end{pmatrix}
$$

where Z is the optical axis.

I have developed a second LabView program to control the NI and PI boards. It is able to control the piezo elongation both in open loop and in closed loop. It also show the distance data from the capacitive sensor read through one of the analog inputs of the NI board. It is possible to set the piezo elongation manually or to use an automatic loop feeding a stepped triangular signal to the piezo. The latter provides a progressive elongation of the piezo actuator with the desired number of steps, and subsequent return to the rest position. Even in this case the program can control one actuator at a time. The system can be easily adapted to control all the actuators at the same time and perform the spectral scan.
Chapter 4

Test Results and Conclusions

In order to test the reliability of the opto-mechanical actuator, both in closed and open loop operation mode, I realized an appropriate device. The piezo actuators are the most important component of the prototype, because they make the spectral scan possible. The reliability of the instrument is mostly based on piezo actuators functioning. The test device uses one piezoelectric actuator and one capacitive sensor to control a rotating mechanism on which a mirror is mounted. The mirror deviates a laser beam and, using an optical lever, it is possible to measure the actuator elongation with submicron resolution. I designed this device to test the actuator in a controlled situation on the optical bench and to develop the dedicated software too. At the end of this chapter I discuss the general conclusions on the prototype.

4.1 The CLAMP Test for Single Piezo Servo Control

The device has the aim to test a single actuator in a servo controlled closed loop operation mode. Hence the acronym CLAMP: Closed Loop Actuator Mono Piezo. CLAMP has an external steel case open two sides (see fig. 4.1). The device includes a linear translation stage moved by the actuator by pushing on the inner wall of the case. The actuator is housed in a custom small case screwed to one end of the linear stage. The actuator case is open on the left side only (referring to the figure 4.1). On that side the actuator has a ball-tip which pushes against the case wall.
Figure 4.1: CLAMP: rear view. On the left the small metal case housing the piezo actuator. Attached to the top of the case, the Newport linear translation stage. On the lower right end of the linear stage the “L” shaped target metal plate. On the right, emerging from the right panel of the case, the capacitive sensor.

Figure 4.2: CLAMP: front view. On the right the arm with the mirror. The pin connecting it to the actuator case is visible too.
An arm, mounted with a pin on the lowest part of the actuator case, transforms the translation motion in a rotation. The arm is held against an external edge of the CLAMP case. I mounted a mirror on the arm to deviate a laser beam (see picture 4.2). Then I obtain the actuator elongation measuring the displacement of the laser image. The beam is produced using a Melles Griot class IIIb (30 mW) Helium-Neon laser operating at 632.8 nm. The beam is used on the same optical bench for other purposes too. A collimated beam is produced using a 20 µm pinhole and a collimating lens positioned at its focal distance (250 mm) from the pinhole (see fig. 4.3). Then, two mirrors deflect the laser beam and the beam size is shrunk to a diameter of 4 mm for other purpose. After that a beam splitter is used to take half of the beam photons and point them to the CLAMP mirror.

![Figure 4.3: Optical Bench Setup for CLAMP. Laser beam deflections and CLAMP are visible. On the far right the camera used to take data](image)

The CLAMP mirror is at a ~ 45° with respect to the incoming beam, redirecting it to an imaging lens with a focal length of 1.000 ± 0.001 m. This focuses the laser beam on a CCD camera. The latter is a BCi-5 C-CAM Technologies with 1280x1024 pixels and a pixel size of 4 µm.

Following the scheme shown in fig. 4.4 it is possible to compute the actuator elongation \( X \) starting from the measure of the displacement of the laser beam \( d \). Data used are:

- \( x \), actuator elongation to be measured
- \( a \), length of the piezo and the piezo case, from the ball-tip end to the pin connected to the arm. \( a = 27 ± 2 \text{ mm} \)
- \( b \), distance of the arm edge contact from the piezo axis, \( b = 20 ± 2 \text{ mm} \)
• $d$, displacement of the laser beam on the CCD camera, 1 pixel = $4.00 \pm 0.01 \mu m$

• $\alpha$, mirror tilt angle produced by the actuator displacement

• $f$, focal length of imaging lens, $f = 1000 \pm 20 mm$

![Diagram of CLAMP Scheme](image)

Figure 4.4: CLAMP Scheme. $a$ is the length of the piezo, $x$ the elongation, $b$ is the distance between the edge that acts as sliding contact point and the hinge of the arm, $\alpha$ is the angle deriving from piezo elongation.

From trigonometric computations $\alpha$ can be computed as

$$\alpha = \arctan \left( \frac{-bX}{a(a + X) + b^2} \right) \simeq \frac{-bX}{a(a + X) + b^2} \simeq \frac{-bX}{a^2 + b^2} \quad (4.1)$$

Since the differential angle of incidence of the beam due to the mirror rotation is $2\alpha$, the displacement of the beam on the focus plane is $2\alpha f$. So we have

$$d = -\frac{2bfX}{a(a + X) + b^2} \quad (4.2)$$

and the piezo actuator elongation is

$$X = -\frac{d(a^2 + b^2)}{ad + 2bf} \quad (4.3)$$

Given the measured properties of the CLAMP test, for a displacement of 1 pixel on the CCD camera is obtained:

$$X = (0.112 \pm 0.012) \mu m \quad (4.4)$$

You can find the discussion about errors in §4.1.
Instrumental Setup and Software Control

In the following scheme (fig. 4.5) I describe the control system for CLAMP test. The NI board is controlled with a LabView program by a PC. This electronic board produces the analog control signal for the PI board. BNC and LEMO cables are used to carry the signals all along the CLAMP setup. A probe performs a check on the low voltage output from the NI board. Signal is the amplified using the PI board. This high voltage output is fed directly into the piezo electrodes in case of an open loop operation. Otherwise, the signal is processed internally by the PI board, in dedicated servo-circuits, using the signal from capacitive sensor to correct the voltage output. I also verified this high voltage signal with a probe. I carefully controlled common ground of all electronic apparatus in order to avoid spurious signals. I inspected cables resistance to be $< 0.3 \, \Omega$.

![CLAMP system control scheme](image)

Figure 4.5: CLAMP system control scheme

In case of closed loop operation, the gap between the capacitive sensor and the target plate must be carefully set to 50 $\mu m$. The required precision in the sensor positioning is $\pm 25 \mu m$. Exceeding those values results in the impossibility to reliably close the servo loop. Calibrated spacers of 13.3 $\mu m$ have been used for this purpose. Capacitive Sensor zero potentiometer has to be checked daily before the start of the operations in order to center the working range of the signal. Another issue is the maximum accepted tilt between the sensor plate and the target plate; it must be less than 0.7 $mrad$ to obtain a linear response from the sensor. The output of the sensor is 0 $\div 10 \, V$ and correspond to an absolute measure of the distance after the manufacturer calibration.

I find the beam displacement computing the centroid position of the beam image, thus achieving subpixel resolution. The images are acquired using a dedicated subroutine of the
piezo control program written in LabView (see appendix B.3). Then I analyse the image sequences using the IDL program reported in appendix B.2 to compute the centroids. Using the first computed value of the centroid as a reference, the displacement in pixels is obtained.

Some screenshots of the LabView actuator control can be found in appendix B.3. The program is able to control the actuator giving a voltage or a displacement input in manual mode. It has also an automatic function to extend the piezo in steps, coming back to the home position once completely extended. It shows the measured value of distance from the capacitive sensor and is able to the take images of the beam, synchronizing data acquisition with piezo step elongation.

**CLAMP MK I and MK II**

The first model of CLAMP (see fig. 4.6) had the capacitive sensor mounted on the linear stage. The target plane was one of the inner walls of the CLAMP case. This kind of design had a defect: the sensor together with the LEMO cable used to collect the signal move while the actuator extends. Changes in the cable curvature may introduce time variable parasitic capacitance that could affect distance measures. In order to avoid this effect a new design has been devised, with sensor and cables fixed to the CLAMP case wall, the CLAMP MK II (fig. 4.7). In this model the sensor target is a steel plate screwed to the linear stage.

![Figure 4.6: CLAMP MK I](image)

Figure 4.6: CLAMP MK I: the capacitive sensor is mounted on the linear stage, using one wall of the case as a target.
Figure 4.7: CLAMP MK II detail: the capacitive sensor is mounted on the wall of the case. A dedicated steel made target is mounted on the linear stage. The image shows the working distance of the CLAMP MK II system of 45 $\mu$m between the probe and the target.

Errors and Noise level

I computed the absolute error on the evaluation of the piezo elongation using error propagation theory, deriving:

$$
\Delta X = \frac{1}{(ad + 2bf)^2} \sqrt{d^2(d(b^2 - a^2) - 4abf)^2 \Delta a^2 + 4d^2(abd + f(b^2 - a^2))^2 \Delta b^2 + \\
... + 4d^2b^2(a^2 + b^2)^2 \Delta f^2 + 4b^2f^2(a^2 + b^2)^2 \Delta d^2} 
$$

(4.5)

In the following plot, the trend on the elongation error as a function of the precision on the other distances measured, is shown. 100% correspond to the actual precision achieved. From the plot we can evince that the main contributor to the measure error is the piezo length $a$.

Figure 4.8: Absolute errors trend for the different measure contributions as a function of the different measure errors. 100% correspond to actual absolute error for that distance.

I studied the general noise level of the CLAMP setup for different cases. The optical bench has an air cushion suspension in order to reduce the external vibration influences. Nevertheless, a certain amount of vibrations is always present, from the optical system, and possibly from
the piezo actuator itself. Another possible source of noise may be the variation of the condition of air on the optical bench, resulting in “seeing” disturbing the measures. Here I present two datasets of noise analysis. They contain data acquired with CLAMP fixed on a static position in order to measure the noise level only.

The first contains data from two runs of 200 s each, one for the open loop (fig. 4.9) and one for the closed loop operations (fig. 4.10). Displacement values for the x and y axis of the camera are shown as a function of the image number. In figure 4.11 the centroid position evolution for the open loop is shown. Equivalent data are shown in figure 4.12 for the closed loop. It is clear that the closed loop is affected by a higher level of noise as the diameter of the circle describing the position evolution is almost twice that of the open loop.

Figure 4.9: Open loop: x (top) and y (bottom) noise. On the horizontal axis image number is reported. On the vertical axis there is the centroid displacement with respect to the first image.
Figure 4.10: Closed loop: x (top) and y (bottom) noise. On the horizontal axis image number is reported. On the vertical axis there is the centroid displacement with respect to the first image.

Figure 4.11: Open loop position evolution. On the horizontal and vertical axis, x and y displacement are shown, in pixels
In order to further investigate the noise source a new dataset has been recorded. It contains four series of data, characterized by different conditions:

1. The air suspension of the optical table was turned off. All electronics of the system was turned off.
3. Piezo actuator in open loop operation mode, fixed position during all the acquisition.
4. Piezo actuator in closed loop operation mode, active fixed position during all the acquisition.

The first measure is intended to investigate external source of vibrations and the subsequent reduction when the bench is on. The second is a check on the seeing conditions on the table, air flow would supposedly be the biggest source of noise in this case. The CLAMP is off and its mirror cannot move. The third measure is in open loop operation, electronic noise may cause spurious movements due to unwanted peaks in the driving analog signal. In the fourth measure the servo loop is active and the position of the mirror is maintained fixed with the active control of the capacitive sensor servo mechanism. A drift in the displacement data is found in this dataset.

For each series of data are shown image of the position evolution of the beam on the CCD (fig. 4.13 4.17 4.21 4.25), x and y displacements as a function of the progressive image number (fig. 4.14 4.15 4.18 4.19 4.22 4.23 4.26 4.27), a drift corrected image of the displacements of the beam (fig. 4.14 4.15 4.18 4.19 4.22 4.23 4.26 4.27) and a Gaussianity plot of the displacement on both the axis (fig. 4.16 4.20 4.24 4.28). Noise number defining the data series refers to the previous enumeration.
Figure 4.13: Noise data 1: position evolution of the beam on the CCD.

Figure 4.14: Noise data 1: x-axis noise with linear fit of the drift (top). Fit: drift(pixels) = $(-0.29 \pm 0.02) + (0.0025 \pm 0.0001) \cdot in$ (image number). x-axis noise corrected for the drift, $\sigma_x = 0.24$ (bottom).
Figure 4.15: Noise data 1: $y$-axis noise with linear fit of the drift (top). Fit: $\text{drift(pixels)} = (-0.31 \pm 0.04) + (-0.0101 \pm 0.0002) \cdot \text{in (image number)}$. $y$-axis noise corrected for the drift, $\sigma_y = 0.42$ (bottom).

Figure 4.16: Gaussianity fit of the noise. $x$-axis: $\chi^2 = 30.8$ (top). $y$-axis: $\chi^2 = 21.1$ (bottom)
Figure 4.17: Noise data 2: position evolution of the beam on the CCD.

Figure 4.18: Noise data 2: x-axis noise with linear fit of the drift (top). Fit: drift(pixels) = \((-0.30 \pm 0.03) + (0.0028 \pm 0.0001) \cdot \text{in} \) (image number). X-axis noise corrected for the drift, \( \sigma_x = 0.28 \) (bottom).
Figure 4.19: Noise data 2: y-axis noise with linear fit of the drift (top). Fit: \( \text{drift(pixels)} = (0.62 \pm 0.04) + (-0.0071 \pm 0.0001) \cdot \text{in (image number)} \). y-axis noise corrected for the drift, \( \sigma_y = 0.38 \) (bottom).

Figure 4.20: Gaussianity fit of the noise. x-axis: \( \chi^2 = 16.3 \) (top). y-axis: \( \chi^2 = 14.4 \) (bottom)
Figure 4.21: Noise data 3: position evolution of the beam on the CCD.

Figure 4.22: Noise data 3: x-axis noise with linear fit of the drift (top). Fit: drift(pixels) = (0.32 ± 0.05) + (0.0027 ± 0.0002) · in (image number). x-axis noise corrected for the drift, $\sigma_x = 0.49$ (bottom).
Figure 4.23: Noise data 3: y-axis noise with linear fit of the drift (top). Fit: drift(pixels) = \((-0.02 \pm 0.06) + (-0.0048 \pm 0.0002) \cdot in\) (image number). y-axis noise corrected for the drift, \(\sigma_y = 0.56\) (bottom).

Figure 4.24: Gaussianity fit of the noise. x-axis: \(\chi^2 = 5.7\) (top). y-axis: \(\chi^2 = 10.5\) (bottom)
Figure 4.25: Noise data 4: position evolution of the beam on the CCD.

Figure 4.26: Noise data 4: x-axis noise with linear fit of the drift (top). Fit: $\text{drift (pixels)} = (-0.8 \pm 0.1) + (0.0014 \pm 0.0004) \cdot \text{in (image number)}$. x-axis noise corrected for the drift, $\sigma_x = 1.01$ (bottom).
Figure 4.27: Noise data 4: y-axis noise with linear fit of the drift (top). Fit: drift(pixels) = (0.7 ± 0.1) + (−0.0021 ± 0.0005) · in (image number). y-axis noise corrected for the drift, \( \sigma_y = 1.22 \) (bottom).

Figure 4.28: Gaussianity fit of the noise. x-axis: \( \chi^2 = 8.7 \) (top). y-axis: \( \chi^2 = 4.9 \) (bottom)
Noise Interpretation

A mechanical source of noise deriving from the piezo actuator itself has been proposed as the reason for the bigger noise level in the closed loop data series of the first dataset (see fig. 4.11, 4.12).

This is investigated using the second dataset. Since the total length of the laser beam exceed 7m it is not clear how much the first measures were affected by air flows on the optical bench. For this reason air conditioning in the laboratory was turned off. This resulted in a progressive rise in the room temperature of 4°C during the day of the second dataset acquisition. A drift in the displacement data is found in this dataset. Such drift value is compatible with a thermal expansion of the steel case:

As it is clear comparing linear fit parameters from the four datasets, drift is of the same order in the first three cases. When the servo control is on, the sensor measure the distance in real time and it seems to succeed in correcting the drift effect. Comparing the dispersion of the displacements, this increases with the series number. So it seems that same kind of mechanical noise is introduced while the actuator is active. The active suspension does not seem to decrease the mechanical noise from outer sources. Therefore internal sources of mechanical noise has an higher amplitude than the external ones. It is evident that thermal stability and mechanical damping of vibrations must be considered in the final setup of the prototype.

\[
\alpha = \frac{1}{L} \frac{dL}{dT} \quad (4.6)
\]

\[
\alpha_{\text{STEEL}} = 17 \times 10^{-6} K^{-1} \quad (4.7)
\]

Using the displacement corresponding to 1 pixel as \(\Delta L\) and the case dimension (18 cm) as \(L\):

\[
\Delta T \approx \frac{\Delta L}{L} \alpha^{-1} = \frac{1 \times 10^{-7}}{18 \times 10^{-2} \times 17 \times 10^{-6}} = 3 \times 10^{-2} K \quad (4.8)
\]

A change in temperature of 0.03 K over two minutes of data taking is a plausible explanation of the drift observed.

Open Loop Data Analysis

I made open loop measures using 1 V steps from \(-1 V\) to 10 V as low voltage driving signal. I have taken 40 images for every actuator position with 8 ms of exposure time and a wait time of 500 ms from one image to the other. 22 points in total were recorded (fig. 4.29). Each point represent the mean value over 40 images of the displacement in pixels. Reported error is \(\pm 1\sigma\)

The hysteresis cycle of the piezo is evident (see fig. 3.17): bottom points refers to piezo elongation while top points refers to piezo retreat. Maximum elongation is 126 \(\pm\) 2 pixels corresponding to 14.1 \(\pm\) 0.2 \(\mu\)m, which is near the nominal value of 15 \(\mu\)m.
Figure 4.29: Open loop: mean data points with error bars (top), continuous line to point out hysteresis (bottom).
Closed Loop Data Analysis

I also made closed loop measures using a reduced control voltage range, still able to cover the full range of piezo extension. 0.5 V steps from 1.5 V to 5.5 V were used as low voltage driving signal. I have taken 40 images for every actuator position with 8 ms of exposure time and a wait time of 500 ms from one image to the other. 16 points in total were recorded. Each point represent the mean value over 40 images of the displacement in pixels. Reported error is ±1σ.

Figure 4.30: Closed loop: mean data points with error bars (top), continuous line to point out linearity (bottom).
The hysteresis has been eliminated respect to data presented in figure 4.29. A zero point difference remain between the elongation (top points) and retreat (bottom points), which follows two different straight lines. A linear fit is computed obtaining figure 4.31 for the elongation points and figure 4.32 for the retreat points. The linear fit parameters are reported in the captions. Slope values are compatible, confirming a zero point difference only between the two lines.

Figure 4.31: Elongation points linear fit (top). \((-48.3 \pm 0.6) + (32.6 \pm 0.2) \Delta V \chi^2 = 2.48\). Residuals of the linear fit (bottom).

I recorded another series of measures with 5 subsequent cycles of elongation and retreat to control if the piezo was still following two different straight lines. I performed measures immediately after the second dataset of noise analysis and are therefore affected by the same
Figure 4.32: Retreat points linear fit (top). \((-36.8 \pm 0.6) + (32.3 \pm 0.2) \Delta V \chi^2 = 1.17\). Residuals of the linear fit (bottom).
thermal drift. Except for this latter effect the previous behavior of the actuator was confirmed, zero point difference between elongation and retreat path included. In this case 1 V steps from 2 V to 5 V were used as low voltage driving signal. Other parameters were the same as the other closed loop measure. Points are shown in figure 4.33. We underline here that in the last plot points are slightly moved horizontally to avoid overlap, only for a graphical necessity. They are all referred to the nearest integer.

Figure 4.33: Closed loop: mean data points with error bars (top), with continuous line to point out extension/retract cycle. Data is also shown as a function of driving voltage (bottom); Points are slightly moved horizontally to avoid overlap, they are all referred to the nearest integer.
CLAMP Results

The nominal maximum extension of the piezo was proved with submicron resolution. The measured value is $14.8 \pm 0.2 \mu m$ in closed loop mode. I obtained open loop and closed loop plots comparable to the functioning data provided by the manufacturer (see img. 3.17). The sensor positioning proved to be extremely important for loop closure, requiring calibrated spacers of $\sim 10 \mu m$.

It is worth to note that, in the case of the open loop, retreat points are above the elongation points, while in the closed loop is the opposite. This issue, probably due to a mechanical backlash of the arm, has to be further investigated, but is a minor problem for the mechanism of spectral scanning since it is performed elongating the piezo in small steps and then returning to home position, following only the top straight line.

On the other hand, linearity, which is the key aspect to control the optical gap, has been verified and confirmed.

More test are required on thermal and mechanical stability over long times before before moving to the construction of the prototype.

4.2 Conclusions

In this thesis we have presented the design of a laboratory prototype Capacitance Stabilized Fabry-Pérot interferometer. I have shown key properties of a spectrometer based on a Fabry-Pérot. A comparison with other types of spectrometer was made, pointing out strengths and weaknesses. Multiple beam interferometry was studied in order to include effects deriving from defects and optical irregularities. In this way, we have proposed a real Fabry-Pérot numerical model and I have implemented a simulation software.

We have discussed the mechanical, electronic and optical characteristics of the prototype in details, with the main idea that this instrument is intended to be a test prototype to prove components reliability. Furthermore, this prototype has the goal to gain experience on the hardware and software problems of a Fabry-Pérot on a model with great parameter flexibility, before the construction of a space version. In particular, we have proved the reliability of the base components of the prototype: the servo controlled piezo actuators together with the capacitive sensors. These are the technologies that can make the instrument stable and reliable. The CLAMP test provided the nominal extension and linearity data necessary to qualify these components for the prototype use.

This work was presented at the “Solar Physics and Space Weather Instrumentation IV” of the “Optics+Photonics 2011” SPIE conference in San Diego. Proceeding paper ca be found in appendix A.
4.3 Future Developments

The manufacture of all the components is nearly complete. The assembly phase is scheduled for October 2011 and testing is due to start before the end of 2011.

We planned optical qualification test with the use of monochromatic laser source and other incoherent sources. We will use a classical mount configuration with an H-alpha interference prefilter (BW 0.07 nm). Spectral profile of this latter will be measured using a monochromator. The ring system obtained with the incoming laser beam will be used for parallelism alignment too, as well as, for gap measures from the diameter of the peak circles. Other measures will be performed using spectral calibration lamps (hydrogen, helium and argon, three gases with strong emission lines in the instrument spectral range). The optical configuration is collimated.

Furthermore, we plan to make a prototype space implementation of the present interferometer in order to start space qualification tests. The design of the latter will be very different with respect to the test prototype. The more demanding operating environment requires a stiffer structure able to keep the alignment during the satellite launch and to compensate for the high thermal variations.

The double adjustment mechanism, involving the possibility to extend the operating FSR, cannot be used because of the extremely reduced operating distance of the capacitive sensors and the use of compliant flexures and springs. Mechanical vibrations and high thermal loads are sources of misalignments that have to be compensated during the different stages of the mission. Moreover manufacturing processes may introduce other potential sources of misalignments. In order to minimize these effects, a good solution is to house both the optical plates in a one-piece optomechanical structure. The monolithic structure avoids connections between separate parts that experience mechanical vibrations, and is made of one material, which removes thermal expansion coefficient differences. Piezoelectric actuators can be housed in this monolithic structure directly, making the interferometer design compact and reliable.

The chosen material is Invar, a nickel-steel alloy having an extremely low thermal expansion coefficient. Optical plates, made of fused silica, will be connected to the optomechanical hardware using low outgassing adhesive which can operate in a vacuum environment.

Special care has to be paid to decouple vibrations induced by the spacecraft and the interferometer natural frequencies; moreover, in order to reduce the amplitude of the vibrations which can damage both optical elements and piezoelectric actuators, a suitable mechanical damping device will be studied.
Postfazione

Così all’istituto di Fisica ottenni una stanza tutta mia, piena di un mucchio di strumenti ottici sensibili. Non tedierò il lettore con la descrizione dei principi e della metodologia di quegli esperimenti, e citerò solo il cosiddetto “interferometro”, costituito da due lastre di vetro semi-riflettenti che devono essere mantenute parallele con la precisione di un milionesimo di centimetro. Dopo averle allineate con grande fatica, basta starnutire e l’allineamento è irrimediabilmente alterato! Li chiamavo i diavoli di entrata e di uscita.

George Gamow, La mia linea di Universo

Se persino Gamow ha trovato così diabolici questi strumenti non si può non ammettere che questi interferometri a cavità ottica risonante siano proprio delle brutte bestie da trattare... D’altro canto 112 anni dopo la loro invenzione rappresentano ancora una sfida tecnologica non banale da vincere. Se da una parte le moderne tecnologie, l’elettronica in particolare, aiutano moltissimo nel controllare questo tipo di strumenti così complicati, dall’altra risulta quasi impensabile che già nel 1924 controllare la cavità ottica con una precisione di 10 nm fosse un’operazione di routine, sebbene difficile. Questi strumenti sono tanto più intriganti se si considera che sono spesso usati come metri campione per le misure più precise. Calibrare tale strumento diventa quindi l’equivalente di ricostruire in casa un metro campione come quello conservato vicino Parigi, senza avere altro standard se non la luce stessa che si vuole filtrare.

La mia tesi consisteva proprio nel descrivere le basi teoriche e i metodi alla base di questi strumenti. Spero di non avervi tediato troppo, d’altronde il mio scopo era ben diverso da quello di Gamow!

Luca Giovannelli
Sono passati sette anni da quando sono entrato in questa facoltà (il che significa che nel computo ci sono due anni di troppo) e sento che questo momento è un po’ una conclusione di un percorso e l’inizio di un altro. Potrei quasi dire che, in modo figurato, ho finito la mia passeggiata per il lungo corridoio di SOGENE… ad ogni modo temo che dovrete sopportare la lettura di questo mio tirare le somme visto che tra le righe cercherò di ringraziare tutti quelli che in questo percorso mi hanno accompagnato.

Anzitutto devo ringraziare tutto il Gruppo di Fisica Solare. Devo dire che tutte le tesi che mi erano state proposte mi allettavano molto, quella che ho scelto era sicuramente la più complessa dal punto di vista pratico, ma anche la più interessante e ricca di opportunità per il futuro. Di una cosa ero e sono convinto, che tutto quello che sono riuscito a fare su questo strumento così complesso e delicato, un vero diavolo come lo definisce Gamow, lo devo alla sinergia di forze che il gruppo ha profuso nel progetto. Ho ricevuto aiuti e consigli davvero da tutti e così ringrazio (per nome visto che in laboratorio ci si chiama così): Francesco, per l’impareggiabile guida e per avermi sempre seguito; Dario, per l’impagabile presenza ogni qualvolta avevo un problema e per tutte le correzioni del mio inglese maccheronico; Martina, gran parte del lavoro (davvero ottimo) sul prototipo è merito tuo, ma spero d’essere stato d’aiuto nel mettere le lentine; Roberto, sei stato il primo a farmi mettere le mani su un banco ottico e mi hai sempre aiutato; il Prof. Alberto Egidi, per l’impagabile esperienza con l’elettronica e la strumentazione; Arnaldo, i tuoi dolci hanno sempre alleggerito qualunque problema; e poi Marco, Fabio, Marta, Valentina, Stefano, Laura, Alberto, Bart, Silvia.

Fin dal corso della triennale avete sempre avuto il pregio di appassionarmi a quello che fate, trasmettendo l’entusiasmo e i contenuti delle vostre ricerche anche nella didattica. E’ per questo motivo, per l’interesse in quello che fate e per lo stupendo clima umano che vi contorna che fin dalla tesi triennale ho cercato di intrufolarmi nel laboratorio. Spero che questo percorso insieme possa proseguire.

Grazie anche per l’opportunità che mi avete dato di vedere un Fabry-Pérot al lavoro. Le esperienze a Sacramento Peak e a Tenerife sono state davvero utili e uniche. Per questo ringrazio anche Arturo e tutte le persone che mi hanno aiutato allo IAC e al Themis. Un ringraziamento anche a tutta la comunità di fisici solari e tecnici di Sunspot, che mi ha accolto facendomi sentire uno di loro.
Un ringraziamento va anche a Ilaria, Mauro, Fabrizio e Serena dell’Osservatorio Astronomico di Roma che mi hanno introdotto nel mondo della Fisica Solare quando ero ancora all’ultimo anno del Liceo. E’ innegabile che è stata l’esperienza con voi a indirizzarmi verso questo, tra i tanti interessi che avevo.

Da ormai tre anni divido le gioie e i dolori del divulgatore con il gruppo DIVA dell’Osservatorio Astronomico di Roma. Buona parte della mia spigliatezza in pubblico e dimestichezza nel semplificare i discorsi la devo all’esperienza accumulata con voi. Un grazie quindi a Francesco, Marco, Riccardo, Roberto, Gabriele, Silvia, Gianluca, Mena, Fabio.

Altre esperienze davvero formative sono state quelle che mi hanno visto coinvolto dentro ScienzImpresa. Un grazie va a tutti i soci, con la speranza che le nostre nuove attività possano crescere nel tempo.

Non deve essere facile sopportarmi quando trasformo casa in un laboratorio... e non succede di rado. Angela, Roberto, Ilaria, siete il mio punto fermo nella vita. Mi avete sempre spinto nel mio percorso appoggiando le mie scelte. Voglio qui sottolineare che, mia madre è stata tra le poche persone a leggersi tutto questo tomo, facendo un prezioso lavoro di correzione! E insieme con mia sorella mi ha aiutato nella dettatura delle correzioni... Un grazie davvero immenso va a tutta la mia famiglia, anche a chi purtroppo non può essere qui oggi per le congratulazioni. So per certo che siete orgogliosi di dove sono e cosa faccio oggi; il mio pensiero va a voi, sempre con affetto.

C’è poi una seconda famiglia che sopporta me e i miei terribili colleghi (oltre che il proprio stesso figlio) nelle loro bizzarrie. Nino, Elisa, Ilaria, Vincenzo, non smetterò mai di ringraziarvi per la vostra immensa ospitalità e l’affetto che dimostrate.

Non è molto consueto vedere dei compagni di classe del liceo ancora uniti ad anni di distanza dal diploma, ma noi siamo una stupenda eccezione. Ormai ci conosciamo da una vita, eppure non c’è serata passata con voi che non ricordi allegra e spensierata, da veri cretini.

Esco da questa facoltà soddisfatto dei corsi che ho seguito, delle conoscenze che ho acquisito, degli ottimi insegnanti che ho avuto e sentendomi incredibilmente arricchito da tutta l’esperienza. Sopra ogni altra cosa però sono soddisfatto dei colleghi che ho incontrato qui a Tor Vergata, ragazze ragazzi con le menti più acute e fantasiose che io abbia mai conosciuto. A tutti voi devo un grazie enorme, mi avete sempre fatto sentire a casa varcando le porte di questa facoltà di Scienze. Abbiamo diviso le fatiche degli esami, proposto ed esaminato le idee più assurde, chiacchierato di quanto di più distante ci fosse dal nostro percorso di studi, sempre con una buona dose di autoironia. Ho trovato persone straordinarie in ogni campo, capaci di preoccuparsi per il futuro di questo paese con una responsabilità che è difficile trovare anche nelle persone che questo paese lo amministrano. Per quanto è stato possibile abbiamo cercato di portare la cultura prodotta qui dentro anche fuori, alla cittadinanza, riuscendoci con successo in almeno un paio di occasioni. Recentemente siamo saliti persino sui tetti di Roma per difendere l’Università. Ad alcuni sarà sembrato che quei due mesi siano stati tempo
perso, che si sarebbe dovuto impiegare per concludere prima gli studi. E stato invece il periodo di tempo speso meglio nella mia vita, sarò sempre orgoglioso di essere stato li con voi. Un pensiero speciale va quindi anche ai ricercatori della Rete29Aprile.

Molti di voi sono più che semplici colleghi, sono amici cari con cui ho diviso tanti momenti fuori dalla facoltà negli ultimi anni. I volti vicini nel corso degli anni sono cambiati, alcuni hanno cambiato studi, altri hanno iniziato a lavorare, altri ancora sono partiti cambiando città, alcuni mi salutano oggi come affascendatissimi dottorati. Vi ricordo tutti con affetto e doppamente qui vi ringrazio. L’elenco sarebbe troppo lungo ma ognuno di voi sa bene quanto gli devo.

Come non ricordare poi l’altra Scienziata dell’Universo che si laur(e)a con me oggi? Abbiamo diviso tanti esami insieme, punzecchiandoci sempre a vicenda per studiare senza perdere tempo (non sempre con successo) e portando sempre a casa un buon risultato alla fine. Abbiamo diviso insieme tutto questo faticoso periodo di scrittura, sostenendoci quando arrivavamo allo stremo. Non potevamo non laurearci lo stesso giorno. Grazie di tutto!

Un ringraziamento speciale poi va alle tre persone con le quali ho condiviso di più questi sette anni qui, ormai per me sono tre fratelli aggiunti. Non so se avremo fortuna con le nostre idee, magari tireremo su progetti importanti o forse le cose ci porteranno a vivere in posti diversi in futuro. So che rimarremo sempre comunque vicini, con quella immancabile dose di eccentricità e fanciullezza interiore che ci accomuna.

Roma, 30 settembre

Luca Azimuth Giovannelli
## Appendix A

### Prototype Features and SPIE Paper

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Spectral Range</td>
<td>$550 \div 900\ nm$</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>90%</td>
</tr>
<tr>
<td>Effective Finesse</td>
<td>19.2</td>
</tr>
<tr>
<td>Optimal Cavity Gap Range</td>
<td>$0.3 \div 20\ mm$</td>
</tr>
<tr>
<td>FSR Range</td>
<td>$0.72 \div 0.011\ nm$</td>
</tr>
<tr>
<td>RP Range</td>
<td>$17\ 577 \div 1\ 171\ 780$</td>
</tr>
<tr>
<td>FWHM Range</td>
<td>$0.037 \div 0.0006\ nm$</td>
</tr>
<tr>
<td>Transparency</td>
<td>59.8%</td>
</tr>
<tr>
<td>Optical Plates Material</td>
<td>Fused Silica</td>
</tr>
<tr>
<td>Plate Diameter</td>
<td>$25.4\ mm$</td>
</tr>
<tr>
<td>Usable Area</td>
<td>80%</td>
</tr>
<tr>
<td>Thickness</td>
<td>$15\ mm$</td>
</tr>
<tr>
<td>Wedge</td>
<td>$30'$</td>
</tr>
<tr>
<td>Surface Quality</td>
<td>$\lambda/60$</td>
</tr>
</tbody>
</table>

Table A.1: Prototype features
The Fabry-Pérot interferometer prototype for the ADAHELI solar small mission

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ABSTRACT

ADAHELI \textit{A}dvanced \textit{A}stronomy for \textit{H}ELIophysics is a solar satellite designed to investigate the fast dynamics of the solar photosphere and chromosphere performing visible and NIR broad-band and monochromatic observations of selected atomic lines. ADAHELI is an Italian Space Agency (ASI) project, approved for a feasibility study within the ASI Small Missions call. ISODY \textit{I}nterferometer for \textit{SO}lar \textit{DY}namics is a Gregorian telescope and its focal plane suite (FPS). The FPS is composed of a high-resolution fast acquisition system, based upon a tandem of Fabry-Pérot interferometers operating in the visible and NIR regions on selected solar atmospheric lines, a broad band channel, and a correlation tracker used as image stabilization system. In this contribution we describe the Fabry-Pérot étalon prototype, based on the capacitance-stabilised concept, realized in our laboratory to perform preliminary mechanical and optical tests with a view to a future Fabry-Pérot étalon prototype for space application.

Keywords: Fabry-Pérot Interferometer, space telescopes, spectroscopy, solar physics

1. INTRODUCTION

High-cadence and high-resolution spectro-polarimetric observations of the lower solar atmosphere are a key tool to investigate highly dynamic phenomena present in these layers of the atmosphere of our star. A fast camera system and a panoramic and high-transparent spectrometer allow us to obtain a suitable cadence to study high-frequency oscillations and fast-moving plasma present in the solar photosphere and chromosphere. The spatial resolution depends primarily on the diameter of the telescope entrance pupil and on the observed wavelengths. However, as far as the spectrometer is concerned, to completely exploit the ADAHELI telescope resolution, two conditions must be satisfied: the instrument itself must not impair the optical quality of the telescope, and the detector must allow a suitable spatial sampling. Moreover, a high spectral resolving power ($R \geq 200000$) is required to properly analyze narrow photospheric lines and a high temporal resolution (several frames per second) is necessary to investigate highly dynamic solar phenomena. The exposure time must be sufficiently short to satisfy the Nyquist frequency associated with the analysis techniques required to exploit the acquired dataset. A sufficiently large field of view (FOV) is essential to easily study active regions and a suitably extended wavelength range, visible-NIR, is needed to offer a broad option among lines with different diagnostic power. Finally, a high wavelength stability (maximum drift 0.02 pm in 10 hours) is mandatory to provide a good reproducibility of the selected spectral points in long observing runs (e.g., oscillatory phenomena).

To this purpose, the Fabry-Pérot interferometer (FPI) seems to be a good candidate. Actually, thanks to its large area and to the low absorption coefficients coatings this device fulfills the required characteristics. Moreover,
FPIs have high achievable spectral resolution, rapid wavelength tuning, if piezo-scanned, and high stability, if capacitance-stabilised and thermo-stabilized.

A short description of the ADAHELI mission is reported in Section 2, while in Section 3 a description of ISODY, the Gregorian telescope and focal plane suite operating in the visible-NIR spectral range is presented. In Section 4 criticalities of space Fabry-Pérot interferometers (FPI) for ISODY are presented, followed by a description of the design of the FPI prototype in Section 5. Finally, concluding remarks and a short description of a second FPI prototype of the instrument are given in Section 6.

2. THE ADAHELI MISSION

ADAHELI is a small-class low-budget satellite mission for the study of the solar photosphere and the chromosphere and for monitoring solar flare emission. ADAHELI’s design has completed its Phase-A feasibility study in December 2008, in the framework of ASI (Agenzia Spaziale Italiana) 2007 Small Missions Program. GGS SpA was leader industry and University of Rome Tor Vergata was leader scientific institution of the project. During its Nominal Mission (two plus one years) ADAHELI shall constantly point the Sun, except during manoeuvres, eclipses or contingencies. The spacecraft radial velocity in the sunward direction, shall not exceed ±4 km/s, during 95% of the yearly orbit. The initial accuracy in pointing a selected Region Of Interest (ROI) must be a small fraction of the field of view, say < 10 arcsec, to get the ROI within the field of view of the high resolution ISODY telescope. The precision in tracking the ROI must be significantly better, i.e. < 0.1 arcsec for the whole duration of the acquisition, to allow the planned high quality of the image series. This must be achieved by the combined action of the satellite Attitude and Orbit Control Subsystem (AOCS) and of the correlation tracker correction system inside the telescope. The satellite relative velocity with respect to the Sun center shall be known within 1 cm/s. These very challenging requirements, flow down constrain the design of the main instrument, ISODY. Further details on the mission and its requirements may be found in 1, 2.

The satellite configuration is characterized by a prismatic bus with body fixed solar array and payloads mounted as shown in Fig.1. The proposed configuration is compatible with the VEGA launcher.

3. THE FOCAL PLANE ASSEMBLY OF THE ISODY INSTRUMENT

ISODY is designed to obtain high resolution spatial, spectral, and temporal polarimetric images of the solar photosphere and chromosphere. The Focal Plane Assembly of the ISODY instrument comprises two visible-near-infrared science optical paths or channels: the Narrow Band (NB) and the Broad Band (BB) channels,
Figure 2: The optical path and the relative positions of the optical elements/units of ISODIY Narrow Band channel.

as well as the Correlation Tracker (CRTR) channel. The optical path with the relative positions of the optical elements/units for the NB channel is shown in Fig.2 and consist in 25 items and/or assemblies, as briefly described in this paragraph. A dichroic mirror (item DM on the figure) transmits part of the telescope beam towards the BB channel in the wavelength range 530-670 nm and reflects part of the beam to the NB channel in the range 850-860 nm. The principal optical path of the NB channel is formed by three folding mirrors (M4, M5 and M6) and three converging lenses (L1, L2 and L3), which successively collimate the solar and the pupil images. After L2, there are two Fabry-Pérot interferometers (FP1, FP2) used in axial-mode and in classic mount and, between them, a filter wheel (FW) carrying a hole, a dark slide and four interference filters. The principal optical path of the BB channel, simpler than the NB channel, is formed by two small folding mirrors, a re-imaging lens unit, a variable neutral density and a filter wheel, carrying a hole, a dark slide and four interference filters. A variable neutral density adjusts the radiation flux for different wavelengths and different exposure times. The optical path of the CRTR channel is common to the Broad Band channel up to a beam splitter, which provides a separate CRTR channel. All the optical instrumentation is mounted on an Optical Bench of honeycomb with sufficient stiffness to be self-supporting and maintain a good planarity on-ground and in-orbit. The envelope of the complete Focal Plane Assembly is 1600 x 900 x 280 mm. The instrumentation is enclosed in a box of dimensions 1600 x 900 x 200 mm.

Narrow Band specifications of the two Fabry-Pérot interferometers are summarized in Table 1. A Classical Mount (CM) has been adopted for the system. From the spectroscopic point of view this mount, with respect to the telecentric one, has the advantage of a transparency profile with the same shape at all the points of the final image. Moreover, its systematic blue-shift is not difficult to correct, allowing use of larger incidence angles than the telecentric mounting, which needs, on the contrary, small relative apertures to achieve good image quality and spectral resolution. This implies that the CM generally allows a larger FOV.3

Further details on the ISODY instrument may be found in 4.
Table 1: Narrow Band specifications of the two Fabry-Pérot interferometers.

<table>
<thead>
<tr>
<th>Plate parallelism and spacing</th>
<th>Capacity servo-controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>50</td>
</tr>
<tr>
<td>Spacing (mm)</td>
<td>2.290, 0.635</td>
</tr>
<tr>
<td>Reflectivity (%)</td>
<td>93</td>
</tr>
<tr>
<td>Absorption coefficient</td>
<td>≤ 0.002</td>
</tr>
<tr>
<td>Large scale defects (nm)</td>
<td>≤ λ/100(λ = 632.8 nm)</td>
</tr>
<tr>
<td>Small scale defects (nm)</td>
<td>Gaussian σ ≤ 1</td>
</tr>
</tbody>
</table>

4. CRITICALITIES OF SPACE FABRY-PÉROT ÉTALON

The Fabry-Pérot etalon is the basis of most types of medium- to narrow-bandwidth filters and is available in many different configurations. It consists of two transparent plates whose facing surfaces are optically flat and coated with a semi-reflective dielectric coating. The Fabry-Pérot plates are separated by spacers, creating a well-defined optical cavity between the coated surfaces (known as the Optical Path Difference or OPD). The etalon or cavity acts as an optical resonator, promoting interference between the beams of the reflected light within the cavity, depending on the optical path difference. In this way, the etalon allows transmission of light at well-defined wavelengths and angles of incidence to the cavity. The development of narrow-bandwidth optical filter technology for use in space applications requires special qualification levels of temperature cycle/shock, thermal/vacuum and vibration/shock tests.

4.1 Mechanical stability

The two ISODY Fabry-Pérot etalons are controlled and stabilised with a capacitive servo control system of plate parallelism and separation. Each FPI is mechanically mounted in such a way that the opposite plates are parallel (this can be easily done with the precision of a few arcseconds). However, the launch stresses can introduce an unwanted tilt producing a wavelength shift of the transparency profile of a FPI with respect to the other. This shift is zero along the axis of tilt. Instead, it grows larger toward the edge of the field of view. The final effect is a detuning between the two interferometers which produces a deformation of the instrument profile and an uneven obscuration. In Fig.3 the effects due to a tilt between the two FPI is shown. Tilt values equal to 0.1°, with different sign for the two FPIs, have been adopted to best visualize the detuning effects.

In order to maintain the transparency variation within 1% the maximum allowable tilt angle between the two FPIs cannot exceed ±30 arcsec.

4.2 Thermal stability

Changes in length of the piezoelectric actuators, due to temperature variations, are sensed by the electronic control which reacts by changing the Fabry-Pérot cavity OPD. This implies that the OPD, and therefore the position in wavelength of the profile of transparency, is sensitive to temperature. We have two special cases:

1 - The temperature varies in the same way for both Fabry-Pérot etalons. In this case, if $K$ is the thermal expansion coefficient of the actuator, we have:

$$\frac{\Delta \lambda}{\lambda} = \frac{\Delta T}{T} = K$$

since:

$$\frac{\Delta \lambda}{\lambda} = \frac{v}{c}$$

Corresponding to a spurious Doppler speed signal:
Figure 3: Tilt produces a shift in wavelength of the transparency profile. The shift is zero along the axis of tilt, while, in the direction perpendicular to this, it grows toward the edge of the field of view. The effect is a detuning between the two interferometers, which produces a deformation of the profile instrument and an uneven darkening.
The temperature of the two interferometers, which would not necessarily be the same, has to be kept constant within $\pm 0.5 \degree C$ to have a maximum drift of the instrumental profile of $\pm 25 ms^{-1}$. For the calculation we considered actuators made of Zerodur ($K = 0.15 \times 10^{-6} \degree C^{-1}$).

2 - The temperature varies differently for the two FP. In this case the transparency profiles of the two interferometers undergo different wavelength shifts that cause a detuning, a deformation of the instrumental profile and a loss of transparency. In order to keep the transparency reduction of the instrumental below 1%, we have to keep the temperature difference the two FPIs within 5$\degree$C.

5. FABRY-PÉROT INTERFEROMETER PROTOTYPE: DESIGN CONCEPTS

5.1 Introduction

In order to test the reliability of the proposed fine adjustment system, a prototype of the interferometer has been designed for a laboratory test. This prototype shares similar optical and control system components with the final FPI for space application.

The proposed control system for the test prototype allows two levels of adjustment: a coarse one, controlled by micrometers, and a fine one, controlled by piezoelectric actuators. Position errors are measured by high sensitivity capacitive sensors. The double adjustment has been introduced to extend the working range of wavelengths and to compensate possible mechanical misalignments in the test phase. The double adjustment requires a complex optomechanical structure which has been considered only for the test prototype. The Fabry-Pérot etalon for space application will have a reduced spectral adjustment range.

5.2 Hardware

The optomechanics of the laboratory prototype has been designed to house: a 1 inch (2.54 cm) optical cavity, three micrometers, three piezoelectric actuators, three high sensitivity capacitive sensors. The adopted optomechanics has to control and guarantee the parallelism of the etalon optical surfaces during the wavelength scan, within the optical tolerances defined above.

The etalon main dimensions are: external diameter = 2.54 cm, thickness of the optical surfaces = 15 mm. Maximum displacements are 12 mm for micrometers and 15 $\mu$m for piezoelectric actuators. The high sensitivity capacitive sensors working distance is 50 $\mu$m.

The control loop is managed by a dedicated controller, calibrated on the selected piezoelectric actuators and capacitive sensors.

5.3 Requirements

The definition of the optical requirements has already been discussed. Optical parameters constrain the distance between the cavity surfaces and the tolerances on their parallelism, specifying the minimum displacement that has to be controlled by the fine adjustment.

Operating requirements concern the survival of the components and their correct functioning in the operating environment. The test ground-based Fabry-Pérot will be subject to gravity loads; the space Fabry-Pérot interferometer instead will undergo temperature cycle/shock, thermal/vacuum and vibration/shock and severe accelerations during the satellite launch, and will operate in vacuum.

In the case of the prototype interferometer, optical requirements set the operating distance between the etalon surfaces to 10 mm. Using the coarse adjustment this distance can be changed, as the micrometers allow displacements of the order of millimeters, broadening the range of available spectral lines. Main operating requirements concern the minimization of misalignments of the optical surfaces due to gravity load, and minimization of hysteresis at contact areas.

For the space interferometer the operating requirements involve the adoption of a different design, based on a one-piece concept to minimize the number of mechanical parts, the possible different displacements due to thermal loads and to keep the optical system aligned.
5.4 Prototype design

The design of the test prototype is based on two concepts: ease of manufacture and modularity. The main aim of the optomechanics is, apart from compensating gravity deformations, the decoupling of coarse and fine adjustments. Each optical surface is housed in a different component: one of them is fixed to a base plate, the other is housed in a mobile plate which rests on the base plate by the use of a ball-tip screw. The ball-tip screw is coupled with a V-groove in order to allow rotations and the displacement parallel to the optical axis. Adjustments are performed by three micrometers and three piezoelectric actuators placed in a 120°-symmetry around the etalon. The feedback for the control system is guaranteed by the high sensitivity capacitive sensors, placed in a 120°-symmetry on the backside of the piezoelectric actuators. The control system involves the use of a simple program which inputs the scan sequence during the observation, and the use of the loop controller to manage the fine adjustment by the piezoelectric actuators based on the capacitive sensors measurements. Fig. 4 shows a detailed view of the test prototype optomechanical design. In order to realize kinematic couplings, both micrometers and piezoelectric actuators are equipped with ball-tip ends acting on a V-groove. Both the contact surfaces will be made in stainless steel to reduce hysteresis in the contact area. Decoupling of the coarse and fine adjustments is achieved by separating the mobile plate into two concentric rings. Micrometers act on the outer ring, the contact being preserved by the use of three preloaded springs in 120°-symmetry; the inner ring, which houses the mobile optical surface, is controlled by the piezoelectric actuators; the outer ring is connected to the inner ring by three V-shaped flexures. Piezoelectric actuators are kept in place by the use of a third support plate, attached to the outer ring of the mobile plate. Thus, a micrometer displacement moves both the mobile and the support plates, while a piezoelectric actuator displacement will move just the inner ring of the mobile plate. The left panel of Fig. 5 shows the realization of the decoupling. The right panel of Fig. 5 shows the complete assembly of the prototype optomechanics.

Etalon optical surfaces are connected to their relative plate by means of three equally spaced contact areas placed along each cylinder side surface. Each contact area is connected to its plate by a flexure device. A dedicated tool has been studied to assemble precisely the optical surface to its three flexure devices. Many configurations have been studied, using different materials, flexures shapes and retaining springs rigidity. Optical requirements set the maximum displacement allowed at 50 nm along the optical axis. The material
selected for the optomechanical hardware is stainless steel. The main features that have been considered were: a) material cost and availability, b) elastic modulus, c) surface hardness, d) electrical conductivity, e) coupling with off-the-shelf components (screws, springs).

Analyses were performed in two loading conditions: gravity load and actuator displacement. Given the interferometer layout, gravity acts in the direction normal to the base plate, generating unwanted distortion in every operating condition. Unpredicted deflections of the fixed optical surface have to be avoided, for its position cannot be measured during the observations.

With regard to actuators displacements, two typical conditions have been analyzed: frequency scan (or shift, referring to coarse adjustment) and parallelism adjustment. The former load case involves the actuators performing a synchronized correction. The latter involves a change in the mobile optical surface inclination, that is to say a differential actuator displacement to obtain the necessary inclination angle of the optical surface. Optomechanical hardware rigidity resulted as extremely important in the test prototype design. All the components should have a rigid body behavior during the adjustment operations, because the capacitive sensors measurement is taken on the inner ring of the mobile plate (not on the mobile optical surface directly). Furthermore, displacement of the fixed optical surface should be avoided because it cannot be measured directly during observations. At the same time, another important point is the correct design of the flexures connecting the inner and outer rings of the mobile plate. The aim of these flexures is double: i to keep the inner ring in place against the gravity action, ii to create a weak constraint, avoiding interference with the fine adjustment.

Typical and maximum displacements conditions have been studied, both in frequency scan and parallelism adjustments. Results showed that the effect of gravity load on the etalon surfaces is acceptable. The maximum displacement value obtained on the mobile optical surface was about 95 nm in the direction of the gravity load.

5.5 Space interferometer design

The design of the interferometer for space implementation is different with respect to the test prototype. The more demanding operating environment requires a stiffer structure able to keep the alignment during the satellite launch and to compensate for the high thermal loads.

The ADAHELI mission requires the adoption of a double Fabry-Pérot interferometer with 2 inche etalons having different spacings: the former using 2.29 mm, the latter 635 μm. Satellite specifications set the maximum optomechanical hardware volume to 80x80x60 mm (80 mm maximum diameter) for both the interferometers, and the operating and survival temperatures, respectively $+5^\circ C, +30^\circ C$ and $-20^\circ C, +80^\circ C$. The mass of each Fabry-Pérot interferometer cannot exceed 520g. The double adjustment mechanism, involving the possibility to
extend the operating wavelengths, cannot be used because of the extremely reduced operating distance of the capacitive sensors and the use of compliant flexures and springs. Mechanical vibrations and high thermal loads are sources of misalignments that have to be compensated during the different stages of the mission. Moreover, manufacturing processes might introduce other potential sources of misalignments.

In order to minimize these effects, a good solution is to house both the etalon surfaces in a one-piece optomechanical structure. Starting from a cylindrical blank, proper machining can be obtain two rings (one for each etalon) connected by three elastic elements. The monolithic structure avoids connections between separate parts that experience mechanical vibrations, and is completely made of the one material, which removes thermal expansion coefficient differences. Piezoelectric actuators can be housed in this monolithic structure directly, making the interferometer design compact and reliable.

The chosen material is Invar, a nickel-steel alloy having an extremely low thermal expansion coefficient. Etalons, made of fused silica, will be connected to the optomechanical hardware using low outgassing adhesive which can operate in a vacuum environment.

Special care has to be paid to decouple vibrations induced by the spacecraft and the interferometer natural frequencies; moreover, in order to reduce the amplitude of the vibrations which can damage both etalons and piezoelectric actuators, a suitable damping device will be studied.

6. CONCLUSIONS

In this paper, we presented the design of a laboratory prototype Capacitance Stabilized Fabry-Pérot etalon. The manufacture of all the components is nearly complete. We plan to start the assembly in September 2011 and testing is due to start before the end of 2011. We plan to make a prototype space implementation of the present interferometer in order to start space qualification tests.

ACKNOWLEDGMENTS

This work was supported by Italian Space Agency (ASI) Phase A Contract I/020/08/0 ADAHELI. We thank Marco Velli, Luca Rosselli, Alberto Bigazzi, Paolo Sabatini and the ADAHELI Team for their valuable help in supporting the ADAHELI project.

REFERENCES

Appendix B

Software Control and Analysis

B.1 Ideal and Real Fabry-Pérot simulation

Pro fabry_perot
; Simulation of an ideal and a real Fabry-Perot interferometer
; v.1.0 august 2011 by Luca Giovannelli

intensity=dblarr(1107962)

R=0.90d ; Reflectivity
theta=-10.d ; in arcsec
n=1.d ; refractive index

lambda_T=656.3 ; Target wavelength; 589.6; 630.1517;
d=1.0d ; in mm

A=0.005d ; mirror absorption coefficient
ds=11.0d ; spherical plate defect in nm (peak to valley)
dg=2.0d ; gaussian plate defect in nm
dp=6.0d ; parallelism defect in nm
theta_div=2.0d ; beam angle of divergence in arcsec (aperture finesse)

restore, '/home/azimuth/IDLWorkspace/tesifp/atlante.save',/v
lambda=Neckel(0,*) ; in amstrongs
spectr=Neckel(1,*)/Neckel(2,*)

theta=theta*2.d!*dpi/(360.d*60.d*60.d) ; in rad
lambda=double(lambda)/10. ; in nm
d=d*10.d^-6. ; in nm
theta_div=theta_div*2.d*!dpi/(360.d*60.d*60.d) ; in rad

ideal_fp=FP(R,n,d,theta,lambda_T)

print,'ideal Fabry-Perot parameters'
print,'cavità FP1 = ', d*10.d^(-6.),' mm'
print,'Reflective Finesse = ', ideal_fp(4)
print,'Resolving Power = ', ideal_fp(5)
print,'FWHM = ', ideal_fp(6),' nm'
print,'FSR = ', ideal_fp(7),' nm'

real_fp=FP_real(R,A,n,d,theta,lambda_T,ds,dg,dp,theta_div)

print,'real Fabry-Perot parameters'
print,'cavità FP1 = ', d*10.d^(-6.),' mm'
print,'Peak transparency', real_fp(0)
print,'Reflective Finesse = ', real_fp(1)
print,'Effective Finesse = ', real_fp(2)
print,'Resolving Power = ', real_fp(3)
print,'FWHM = ', real_fp(4),' nm'
print,'FSR = ', ideal_fp(7),' nm'

;prefilter
pf=0.8*exp(-(lambda-656.28)^2./(2.d*(0.042)^2))

plot,lambda,FP_intensity(R,n,d,theta,lambda) , xrange=[655.0,657.6],/xs;
oplot,lambda, spectr, psym=3
oplot,lambda,FP_real_intensity(R,A,n,d,theta,lambda,ds,dg,dp,theta_div)

end

function FP,R,n,d,theta,lambda
;return a vector fp with inside:
;delta phase, F costant, transmission intensity, order, reflecting finesse,
;resolving power, full width half maximum, free spectral range
delta=4.d*!dpi*n*d*cos(theta)/lambda
\[ I_T = \frac{1}{1 + F \sin^2 (\delta/2)} \]

\[ m = \frac{2n \cos \theta}{\lambda} \]

\[ F_r = \frac{\pi \sqrt{F}}{2} \]

\[ \text{FWHM} = \frac{\lambda}{F \cdot m} \]

\[ \text{FSR} = \frac{\lambda}{m} \]

\[ \text{FP} = [\delta, F, I_T, m, F_r, \text{RP}, \text{FWHM}, \text{FSR}] \]

\[ \text{return, FP} \]

\end

\begin{function}
\text{FP_intensity}(R, n, d, \theta, \lambda) \rightarrow \text{return Fabry-Perot intensity}
\text{delta} = 4n \cos \theta / \lambda \]
\[ F = \frac{4R}{(1 - R)^2} \]
\[ I_T = \frac{1}{1 + F \sin^2 (\delta/2)} \]
\[ \text{return, } I_T \]
\end{function}

\begin{function}
\text{FP_real}(R, A, n, d, \theta, \lambda, ds, dg, dp, \theta_div) \rightarrow \text{return a vector fp with inside: peak transparency, reflecting finesse, effective finesse, resolving power, full width half maximum}
\text{delta} = 4n \cos \theta / \lambda \]
\[ F = \frac{4R}{(1 - R)^2} \]
\[ C_{\text{peak}} = (1 - (A/(1 - R)))^2 \]
\[ m = \frac{2n \cos \theta}{\lambda} \]
\[ F_r = \frac{\pi \sqrt{F}}{2} \]
\[ F_{ds} = \frac{\lambda}{2ds} \]
\[ F_{dg} = \frac{\lambda}{4.7dg} \]
\[ F_{dp} = \frac{\lambda}{\sqrt{3}dp} \]
\[ F_{\text{div}} = \frac{\lambda}{(\theta_{\text{div}}^2)d} \]
\[ F_e = \frac{1}{\sqrt{1/(F_{r^2}) + 1/(F_{ds^2}) + 1/(F_{dg^2}) + 1/(F_{\text{div}^2})}} \]
\[ \text{RP} = \frac{m \cdot F_r}{(1/(F_{r^2}) + 1/(F_{ds^2}) + 1/(F_{dg^2}) + 1/(F_{\text{div}^2}))} \]
\[ C_{\text{finesse}} = 1 - ((1 + R)/2) \cdot (1 - (F_e/F_r)) \]
I_T=C_peak*C_finesse/(1.d +((2.d*F_e/!dpi)^2.d)*sin(delta/2.d)^2.d)
FP_real=[C_peak*C_finesse,F_r,F_e,RP,FWHM]
return,FP_real
end

function FP_real_intensity,R,A,n,d,theta,lambda,ds,dg,dp,theta_div
;return real intensity
delta=4.d!*dpi*n*d*cos(theta)/lambda
C_peak=(1.d -(A/(1.d -R)))^2.
m=2.d*n*d*cos(theta)/lambda
F_r=!dpi*sqrt(F)/2.d
F_ds=lambda/(2.d*ds)
F_dg=lambda/(4.7d*dg)
F_dp=lambda/(sqrt(3)*dp)
F_div=lambda/((theta_div^2.)*d)
;F_e=1.d/sqrt((1.d/(F_r^2.))+(1.d/(F_ds^2.))+(1.d/(F_dg^2.))+(1.d/(F_dp^2.))+(1.d/(F_div^2.))); with aperture finesse
F_e=1.d/sqrt((1.d/(F_r^2.))+(1.d/(F_ds^2.))+(1.d/(F_dg^2.))+(1.d/(F_dp^2.)))+$ (1.d/(F_dp^2.))); without aperture finesse
RP=m*F_e
FWHM=lambda/(F_e*m)
C_finesse=1.d -((1.d +R)/2.d)*((1-F_e/F_r))
I_T=C_peak*C_finesse/(1.d +((2.d*F_e/!dpi)^2.d)*sin(delta/2.d)^2.d)
return,I_T
end

B.2 CLAMP Centroid Analysis

pro centroide_noise 
;Laser spot image analysis. Centroid computation
;v.1.0 june 2011 by Luca Giovannelli

dir='/media/universita/clamp/100811/noise0/
'gen_name=' - 2011 08 10 - 13 58 29'
'ext='.tif'
x_siz=1280
y_siz=1024
num1=0; starting point  
num2=399; ending point  

a=fltarr(x_siz,y_siz)  
b=fltarr(x_siz,y_siz)  
c=fltarr(x_siz/2,y_siz/2)  

x_index=indgen(x_siz)  
y_index=indgen(y_siz)  
n=num2-num1  
shift_data=fltarr(n+1,2)  

for i=0,n do begin  
  num=string(num1+i,format= '(I06)')  
  print, num  
  file=dir+num+gen_name+ext  
  a=(read_tiff(file, R,G,B))  
  ;print, size(a)  
  a=a-min(a)  
  a=a/float(max(a))  
  ;c=rebin(a,x_siz/2,y_siz/2)  
  ;tvscl,c  
  ;wait,0.5  
  ;------------------------------------------------------  
  soglia=mean(a)+10*stddev(a)  
  b(*,*)=a gt soglia  
  ;c=rebin(b*a,x_siz/2,y_siz/2)  
  ;tvscl,c  
  ;stop  
  ;wait,0.3  
  ;-----------------------------------------------  
  ;calcolo il centroide  
  tot=total(b*a)  
  tot_righe=total(b*a,1)  
  tot_colonne=total(b*a,2)  
  xcen=(total(tot_colonne*x_index))/tot
ycen = (total(tot_righe*y_index))/tot
; print, xcen, ycen
; print, xcen/2, ycen/2
;------------------------------------
if (i gt 0) then begin
  shift_data(i-1,0) = x_0-xcen
  shift_data(i-1,1) = y_0-ycen
endif else begin
  x_0 = xcen
  y_0 = ycen
endelse
endfor

; plot, indgen(n+1), shift_data(*,0)

end
B.3 LabView Control programs

Figure B.1: LabView Visual Interface for Thorlabs micrometer control
Figure B.2: LabView code for Thorlabs micrometer control
Figure B.3: LabView Visual Interface for PI Actuator
Figure B.4: LabView Visual Interface for CCD camera control
Figure B.5: LabView code for CCD camera
Figure B.6: LabView code for PI Actuator
Figure B.7: LabView code for PI Actuator
Appendix C

Tables and Technical Drawings

C.1 Thorlabs Z812B Servo Motor Actuator Features

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bidirectional Repeatability</td>
<td>$&lt; 1.5 \mu m$</td>
</tr>
<tr>
<td>Backlash</td>
<td>$&lt; 8 \mu m$</td>
</tr>
<tr>
<td>Maximum Velocity</td>
<td>$3 \text{ mm/s}$</td>
</tr>
<tr>
<td>Recommended Horizontal Load Capacity</td>
<td>$&lt; 7.5 \text{ kg}$</td>
</tr>
<tr>
<td>Recommended Vertical Load Capacity</td>
<td>$&lt; 4.0 \text{ kg}$</td>
</tr>
<tr>
<td>Minimum Achievable Incremental Movement</td>
<td>$0.05 \mu m$</td>
</tr>
<tr>
<td>Minimum Repeatable Incremental Movement</td>
<td>$0.2 \mu m$</td>
</tr>
<tr>
<td>Absolute On-Axis Accuracy</td>
<td>$95 \mu m$</td>
</tr>
<tr>
<td>Home Location Accuracy</td>
<td>$&lt; 2 \mu m$</td>
</tr>
<tr>
<td>Homing Repeatability</td>
<td>$\pm 1.0 \mu m$</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>$-20$ to $65^\circ C$</td>
</tr>
<tr>
<td>Weight</td>
<td>$0.134 \text{ kg}$</td>
</tr>
<tr>
<td>Travel Range</td>
<td>$12.0 \text{ mm}$</td>
</tr>
<tr>
<td>Gear Reduction</td>
<td>$67 : 1$</td>
</tr>
<tr>
<td>Rotary Encoder</td>
<td>512 counts/rev of the motor</td>
</tr>
</tbody>
</table>
|                                      | 34,304 counts/rev of leadscREW |}

Table C.1: Thorlabs Z812B servo motor actuator
C.2  PI PICMA P-887.51 Piezo Actuator and D-510.50 Capacitive Single Electrode Sensor

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>7x7x18 mm</td>
</tr>
<tr>
<td>Maximum Voltage Range</td>
<td>−20 ÷ 120 V</td>
</tr>
<tr>
<td>Operating Voltage Range</td>
<td>0 ÷ 100 V</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>&lt; 150 °C</td>
</tr>
<tr>
<td>Nominal Displacement (@100 V)</td>
<td>15 ± 10% µm</td>
</tr>
<tr>
<td>Blocking Force (@120 V)</td>
<td>1750 N</td>
</tr>
<tr>
<td>Stiffness</td>
<td>100 N/µm</td>
</tr>
<tr>
<td>Electrical capacitance</td>
<td>3.1 ± 20% µF</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td>70 ± 20% kHz</td>
</tr>
</tbody>
</table>

Table C.2: PI PICMA P-887.51 Piezo Actuator

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Gap</td>
<td>25 µm</td>
</tr>
<tr>
<td>Maximum Gap</td>
<td>75 µm</td>
</tr>
<tr>
<td>Nominal Measurement Range</td>
<td>50 µm</td>
</tr>
<tr>
<td>Static Resolution</td>
<td>&lt; 1 pm</td>
</tr>
<tr>
<td>Dynamic Resolution</td>
<td>&lt; 2 pm</td>
</tr>
<tr>
<td>Linearity Error</td>
<td>&lt; 0.1% µm</td>
</tr>
<tr>
<td>Active Area</td>
<td>27.9 mm²</td>
</tr>
<tr>
<td>Operating Temperature range</td>
<td>−20 ÷ 100 °C</td>
</tr>
<tr>
<td>Weight</td>
<td>10 g</td>
</tr>
</tbody>
</table>

Table C.3: PI D-510.50 Capacitive Single Electrode Sensor
C.3 Controllers

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-503.00 Amplifier Board</td>
<td></td>
</tr>
<tr>
<td>Channels</td>
<td>3</td>
</tr>
<tr>
<td>Average Output Current per Channel</td>
<td>60 mA</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>$-2 \div 12 \text{ V}$</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>$-20 \div 120 \text{ V}$</td>
</tr>
<tr>
<td>E-509.00 Servo Module</td>
<td></td>
</tr>
<tr>
<td>Channels</td>
<td>3</td>
</tr>
</tbody>
</table>

Table C.4: PI Controller E-500

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Output Channels</td>
<td>4</td>
</tr>
<tr>
<td>Voltage Range</td>
<td>$-10 \div +10 \text{ V}$</td>
</tr>
<tr>
<td>Digital Resolution</td>
<td>16 bit</td>
</tr>
<tr>
<td>Sample Rate</td>
<td>1.25 MS/s</td>
</tr>
<tr>
<td>Maximum Voltage Range Accuracy</td>
<td>2.08 mV</td>
</tr>
<tr>
<td>Analog Input Channels</td>
<td>16 differential or 32 single ended</td>
</tr>
<tr>
<td>Voltage Range</td>
<td>$-10 \div +10 \text{ V}$</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>50 ns</td>
</tr>
<tr>
<td>Crosstalk (@ 100kHz)</td>
<td>$-95 \text{ dB}$</td>
</tr>
</tbody>
</table>

Table C.5: NI DAC Board USB-6259: Multifunction Digital and Analog I/O
## C.4 Optical Plates

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Fused Silica</td>
</tr>
<tr>
<td>Diameter</td>
<td>25.4 mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>15 mm</td>
</tr>
<tr>
<td>Wedge</td>
<td>30'</td>
</tr>
<tr>
<td>Surface Quality</td>
<td>λ/60</td>
</tr>
<tr>
<td>Dielectric Coating Range</td>
<td>550 ÷ 900 nm</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>90%</td>
</tr>
<tr>
<td>Peak to Valley Defects</td>
<td>10.8 nm</td>
</tr>
<tr>
<td>RMS Defects</td>
<td>1.9 nm</td>
</tr>
<tr>
<td>Usable Area</td>
<td>80%</td>
</tr>
</tbody>
</table>

Table C.6: LightMachinery Optical Plates
### C.5 Fabry-Pérot Simulation

<table>
<thead>
<tr>
<th>Optical Gap 0.3 mm Simulation</th>
<th>Optical Gap 1.0 mm Simulation</th>
<th>Optical Gap 3.0 mm Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ideal Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reflecting Finesse</td>
<td>29.80</td>
<td>29.80</td>
</tr>
<tr>
<td>Resolving Power</td>
<td>27247</td>
<td>90824</td>
</tr>
<tr>
<td>FWHM</td>
<td>0.0241 nm</td>
<td>0.0072 nm</td>
</tr>
<tr>
<td>FSR</td>
<td>0.718 nm</td>
<td>0.215 nm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Real Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak Transparency</td>
<td>59.8%</td>
<td>59.8%</td>
</tr>
<tr>
<td>Effective Finesse</td>
<td>19.23</td>
<td>19.23</td>
</tr>
<tr>
<td>Resolving Power</td>
<td>17576</td>
<td>58589</td>
</tr>
<tr>
<td>FWHM</td>
<td>0.037 nm</td>
<td>0.0112 nm</td>
</tr>
<tr>
<td>FSR</td>
<td>0.718 nm</td>
<td>0.215 nm</td>
</tr>
</tbody>
</table>

Table C.7: Fabry-Pérot Simulation Results
### Simulation Parameters

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflectivity</td>
<td>0.9</td>
</tr>
<tr>
<td>Angle of Incidence</td>
<td>10 arcsec</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.00</td>
</tr>
<tr>
<td>Mirror Absorption Coefficient</td>
<td>0.005</td>
</tr>
<tr>
<td>Spherical Plate Defects</td>
<td>11 nm</td>
</tr>
<tr>
<td>Small Plate Defects</td>
<td>2 nm</td>
</tr>
<tr>
<td>Parallelism Defects</td>
<td>6 nm</td>
</tr>
</tbody>
</table>

Table C.8: Fabry-Pérot Simulation Parameters

### C.6 Prototype Technical Drawings
Tutti i gruppi di forature hanno simmetria a 120°.
SEZIONE A-A
SCALA 2 : 1
dimensioni dello scasso per l'alloggiamento dei pin

SEZIONE B-B
SCALA 2 : 1
dimensioni della guida a V - anello interno

SEZIONE C-C
profondità dello scasso per l'alloggiamento degli adapters

SEZIONE D-D
dimensioni dei fori di alleggerimento e di attacco piastra supporto

SEZIONE E-E
SCALA 2 : 1
dimensioni della guida a V - anello esterno

Piastra mobile
3 - sezioni
Piastra mobile

4 - isometriche

PESO: $PRPSHEET:{Peso}
$PRPSHEET:{Fine}
Acciaio inox A3

FOGLIO 1 DI 1
SCALE: 2:1

N. DISEGNO
TITOLO:

REVISIONI
NON SCALARE IL DISEGNO

MATERIALE:

DATA
FIRMA

QUANTITÀ

QUALITÀ

FATTO
APPROVATO
VERIFICATO
DISEGNATO
Simmetria a 120°

Piastra supporto

1 - front e sezione

A3
Flexures

Acciaio inox

4 fori M1.6 passanti

Se non specificato:
Quote in millimetri
Pintura superficie:
Tolleranze:

Lineari:
Angolari:

Qualità:

Peso: SPRPSHEET(Peso)

Scala: 2:1

FOGLIO 1 DI 1

REVISIONE

MATERIALE:

N. DISEGNO

APPROVATO

VERIFICATO

DISEGNATO
Scatola piezo

M1.6 filettato

Acciaio inox

PESO: $PRPSHEET{Peso}$

SCALA: 2:1

FOGLIO 1 DI 1
1. Clear aperture: 85%
2. S2, S3 Inside Surfaces Matched to: lambda/100 or better
3. S1, S4 Outside Surfaces; lambda/20 or better
4. Uncoated
5. Surface quality: 10/5 or better
6. Wedge: 30 minutes of wedge
7. Indicate max thickness with arrow on side pointing towards matched side
8. Surfaces to be matched with opposing wedges as shown
9. Serialize matched pairs with work order number and -001, 002, 003...

REVISIONS

<table>
<thead>
<tr>
<th>REV</th>
<th>REVISED PER</th>
<th>Date</th>
<th>Approved</th>
</tr>
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<tr>
<td>A</td>
<td>first release</td>
<td>2006/June/6</td>
<td>JHH</td>
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